ARCHITECTURAL VARIATIONS IN RESIDENCES AND THEIR EFFECTS ON ENERGY GENERATION BY PHOTOVOLTAICS

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ARCHITECTURAL VARIATIONS IN RESIDENCES AND THEIR EFFECTS ON ENERGY GENERATION BY PHOTOVOLTAICS

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To my family, Elizabeth Cardona, J. Joaquin Caballero and Carlos Caballero

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LIST OF SYMBOLS AND ABBREVIATIONS

ROI	Return of Investment
EPC	Energy Performance Calculator
NREL	National Renewable Energy Laboratory
USDOE	U.S. Department of Energy
DSIRE	Database of State Incentives for Renewable Energy
GTM	GreenTech Media
EIA	U.S. Energy Information Administration
PV	Photovoltaic
AC	Alternating Current
DC	Direct Current
Mono-Si	Monocrystalline Silicon
Poly-Si	Polycrystalline Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
A-Si	Amorphous Silicon
OPVC	Organic Photovoltaic Cell
BOS	Base of Support
O&M	Operation and Maintenance
SHGC	Solar Heat Gain Coefficient

SUMMARY

In the current global market, there are plenty solutions for the energy savings in the different areas of building consumption: Green roofs and walls, cool roofs, daylighting, motion sensors, and others but there are only very few sources of renewable energy at the reach of a common consumer at residential scale. Photovoltaic systems are the most well-know and reliable technology of harvesting energy at this small scale.

The relationship between energy demand and energy production of a photovoltaic system in a residence is one of the main drivers in decision making while purchasing a system. However, architectural decisions in early stages may influence, enhance or even decrease the possible energy generation and interior performance, thus influencing the possible return of investment. This study evaluates the possible architectural alterations that may beneficial or disadvantageous at a particular city and under other circumstances.

From roof, angle, location, roof articulation, layout articulation , shading devices and others, this paper shows a spectrum of convenient and inconvenient projects due to current conditions like climate, solar radiation, typical construction, electricity rates and government incentives. As a conclusion a hierarchy of architectural elements when being used with photovoltaic technology is developed to demonstrate that a common user can strategically play with architectural features of his/her house to take the most out of the system.

CHAPTER 1

INTRODUCTION

Since the photovoltaic effect was discovered by Edmund Becquerel in 1839, solar panels have become one of the main drivers in trends of new alternative energy generation after hydroelectric and biomass (Ren21 2008). The current necessity of the further exploration of these technologies has been pushed by the sudden rises in gasoline prices and other household expenses that especially to the United States due to the infrastructure and urban planning force the residents' lifestyle to pursuit different alternatives to lower cost utilities. According to PVNord in its article Photovoltaics in Architecture – Lessons learned in PVNord "In most of the projects the technical factor do not seem to have been as determining as the economical factors".

Thus, the lack of practice in fields like Building Integrated Photovoltaics and the low interaction between PV manufacturer and construction market, demands for better studies on this topic (Lundgren 2004).

1.1. Study Overview

The purpose of this study is to evaluate the different possible typical variations of architectural typologies and their effects on photovoltaic systems. Most regions in the United States have their own construction type according to temperature, availability of materials, and passive features. These different variations are represented in the different typologies, which are selected and evaluated in terms of location, radiation level, climate, and construction type. These parameters are the major drivers of the energy generation and demand in each region.

According to the National Renewable Energy Laboratory (NREL) PVWatts Viewer, there are 8 different classifications of radiation levels in the United States: (A) 2.5 to 3.5 kWh/m2/year in main cities like Anchorage, AK. (B) 3.5 to 4 kWh/m²/yr in Seattle, WA (C) 4 to 4.5 kWh/m²/yr in Milwaukee, WI (D) 4.5 to 5 kWh/m²/yr in New York City, NY (E) 5-5.5 kWh/m²/yr in Miami, FL (F) 5.5 to 6 kWh/m²/yr in Los Angeles, CA (G) 6 to 6.5 kWh/m²/yr in Phoenix, AZ and (H) 6.5 kWh/m²/yr and up in Deming, NM. Out of these eight levels, cities have been selected to be analyzed further in this study. The materials and methods of residential construction in the United States vary from wood framing construction to concrete and even metal framing to prefabricated. Each individual state and city has its own set of codes and regulations of these construction methods that organize and addresses at the same time climate requirements while involving passive solutions for less energy consumption.

Additionally, this study evaluates the effects of roof articulation in typologies but also architectural articulation at plan and elevation view when photovoltaics (PV) are placed on the roof. Later PV systems are also evaluated when are placed on the façade and on shading devices to have a wide understanding on the effects of these design decisions.

1.2. Methodology

This computational study is a comparison of the results in energy production and demand in houses equipped with photovoltaic system (PV). Based on radiation level four different locations of the country are selected. For each metropolitan area one typology was chosen in its most basic architectural form to evaluate the energy consumption and demand. Three different sizes (small, medium and large) of that typology will be evaluated to appreciate their difference created in the ratio of energy demand and energy generation and how it has an effect on the system. Thus, a total of 12 case studies will be created and further investigated to effectively compare the technologies and trends to determine which city is most successful in achieving the best results.

The study of a typology is important because their properties vary according to a singular set of conditions corresponding to each region: Insulation is determined by climate conditions, construction technique is determined by availability of local materials, architecture and geometry is also based on each climate, passive strategies and historic influence. All of these are directly related to the energy demand of one residence. Other factors like occupancy, fenestration and size vary according to the necessities of the resident but are factors that also influence this demand. Additionally, the articulation of architecture of a specific typology will be evaluated not only on the roof, but also on the façade and on shading devices in addition to variations on the location, insulation, orientation, etc.

Furthermore, to have a more concrete result in the evaluation of these, the case studies are explored in economic terms. By evaluating the return on investment of these photovoltaic technologies, the study looks for finding the correlation between these different variables and determines the most effective architectural changes when installing a PV system, given the different conditions.

CHAPTER 2

TYPOLOGIES SELECTION BY RADIATION LEVEL: CASE STUDIES

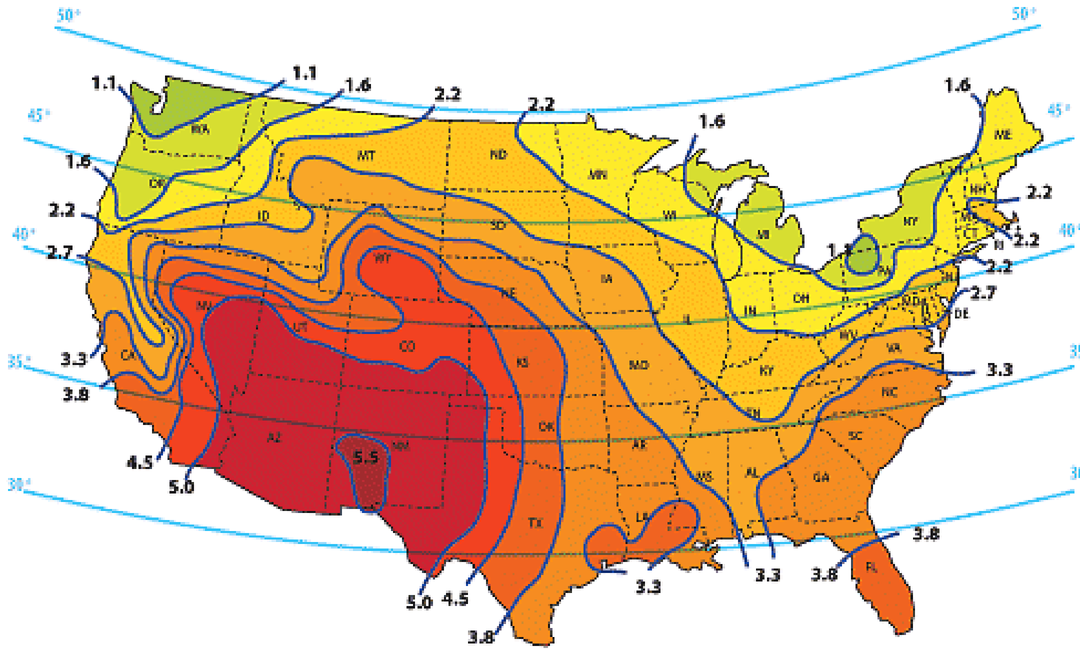


Figure 1. Solar Radiation Levels in the U.S. by Solarcraft

According to the National Renewable Energy Laboratory, there are 8 different levels of radiation in the USA (NREL) and the country has a wide variety of building types that accommodates to each regional climate to compensate for radiation. (Wikipedia) By choosing four cities with different radiation levels we are trying to understand the ramifications of design decisions typical of the area and how they affect energy generation by PVs if incorporated. Additionally different other factors currently helping promote this technology are being evaluated to comprehend the feasibility of the system.

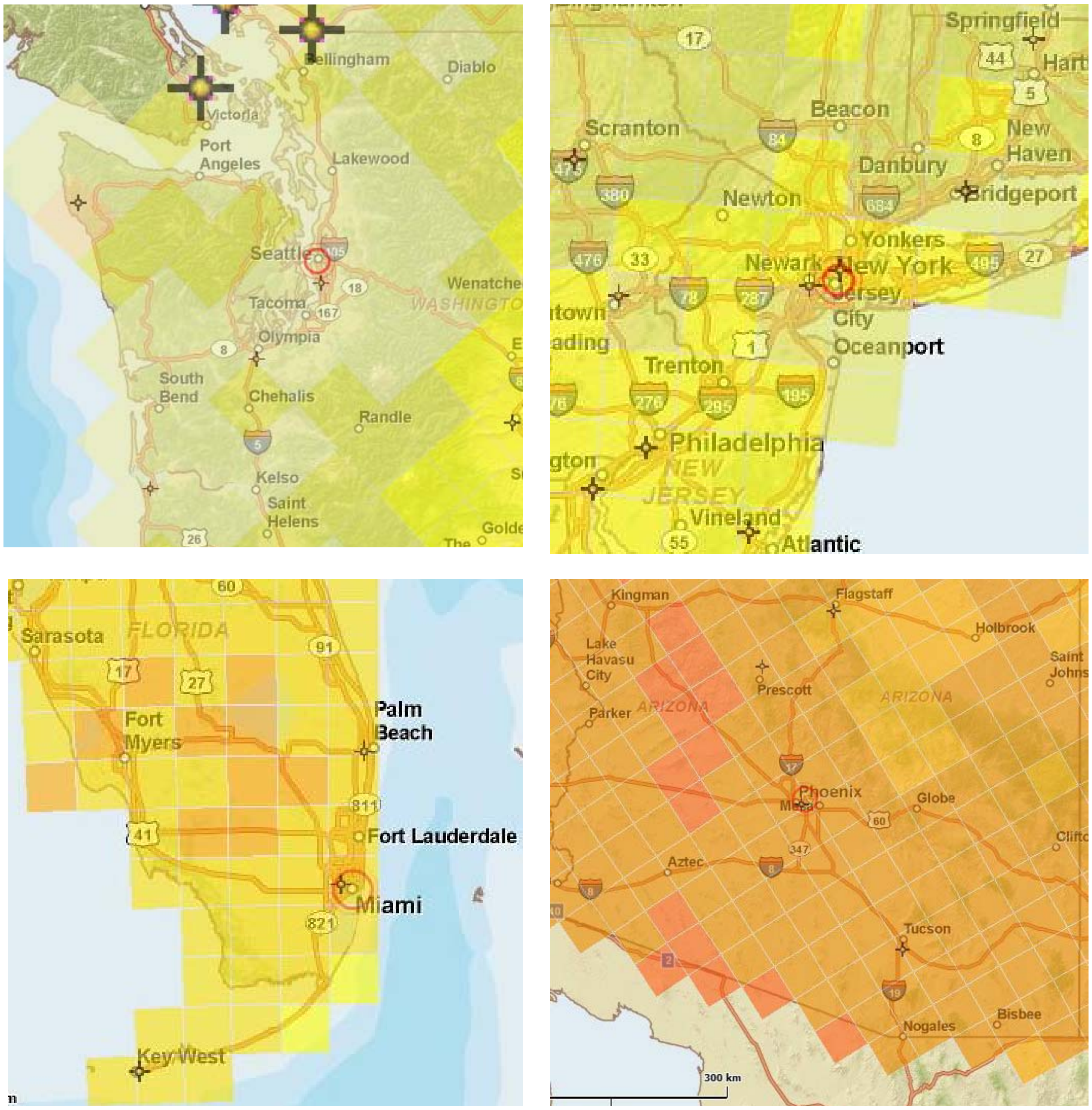


Figure 2. Solar radiation in different cities by PVWatts

2.1. Log House: Seattle, WA

Location

Located in latitude 47º and longitude of -122 º, Seattle, WA is the largest city in the Pacific North West region of the United States (Wikipedia). With a population of 608,660, its weather statistics(USDOE) published by the U.S. Energy Department, is described as oceanic west coast and shows that its average temperature is 5.23°C in winter, 11.52°C in Fall, 10.72°C in spring and 17.37°C in summer, thus being categorized as cool, dry-summer subtropical zone. Its topography is uniformly hilly and vegetation is rich enough consisting of sea, rivers, forests, lakes, and fields.

Radiation Level

According to NREL PVWatts Viewer, Seattle received an approximate solar radiation of 3.6 kWh/m²/yr, which in our study is categorized as level 1 (2.5 to 4 kWh/m²/yr). It has an average electricity rate of 6.72 cents/kWh. However, checking further, electric power in the area is normally provided from Pacific Power , the main electricity supplier of the area and supplier that is going to be used for this evaluation, at a rate of 5.85 cents/kWh, which is drastically lower than the average country rate for February 2011 which was 11.2 cents/kWh (EIA 2011).

Incentives for Renewable Energy

According to the Database of State Incentives for Renewables and Efficiencies (Dsire) from U.S. Department of Energy, the state of Washington offers a 100% sales tax exemption with the purchase of a photovoltaic system. In addition the state government offers and incentive of $0.30/kWh for residential use up to a maximum of US$5,000 per

Figure 3. Yellowstone Club by Locati Architects

year, depending on project type,

technology type and location of manufacturer. The federal incentives consists of 2.2 cent/kWh with no restrictions in time. (DSIRE 2011)

Historic Background and Precedents

Placed in the northern areas of the United States and Canada such as Seattle, log houses have been handcrafted for centuries in Scandivia, Russia and Eastern Europe and the technique was brought in when Swiss and Germans immigrated in a the 17th and 18th centuries (Bomberger 1991). Known as rustic architecture, log houses like the Yellowstone Club by Locati Architects, brings an appearance of simple design decisions forced by the properties of the wood. For example the moisture content and material properties of the log results in a slight shrinking and moving process as the log stabilizes with the weather creating small cracks which gives an appealing and texture to the design (Phleps 1989).

Construction Type

The construction of log houses or cabins is quite intriguing. The connections created to join the different logs, requires them to be shaped in different profiles that interlock with each other to be structurally stable as shown in fig 4. A great deal of craftsmanship is required to construct with other 3 methods of rustic construction:

Figure 4. Log House Connection Joints Samples

(1) Half log: Typical construction where logs are used as veneers in and outside of the building to replicate the original look (2) Palisade: Logs are pinned or bolted together at the corners (3) Piece en piece: The structure of the house is similar to post and beam construction utilizing the logs for this purpose. (Phleps 1989)

In most of these cases, after the log structure is created the interior is fitted with insulation, vapor barrier and other layers of wood or plasterboard as shown on figure 5.

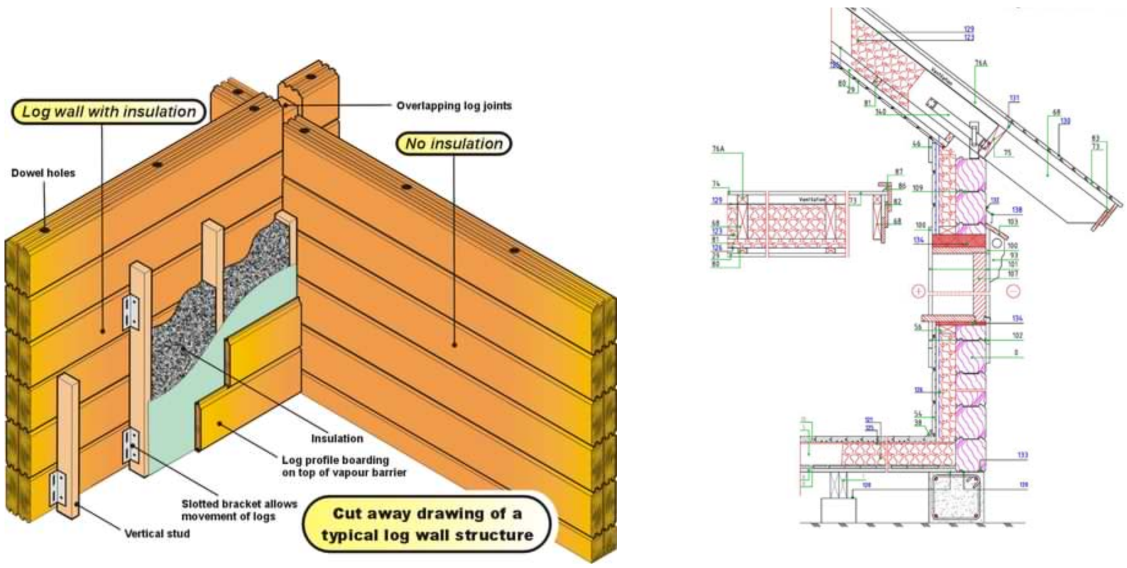


Figure 5. Log House Construction

<u>Roof Type</u>

Historically, the purpose of gabled or triangular roofs have been a practice that intends to create higher spaces on the upper levels of the building while addressing climate conditions like heavy snow. Normally the slope of the roof changes according to the latitude, the higher latitude the steeper slope of roof due to higher tendency of snow precipitation. It is usually recommended to use dark materials for the roof in this climate since they help absorb the heat radiated to the house and thus be more energy efficient (Ching).

Energy Performance

Additionally, according to the Technical Committee of Log Home Council, log homes may be expected to perform 2.5 to 15% more energy efficient than its counterpart in wood framing construction and argues that while a frame wall often has a heat capacity of 0.0002930 kWh/SF, log construction can reach 8 times this capacity over the same surface area (Council 2003)

2.2. Gambrel House: New York City, NY

Location

Located in the north east region of the United States, New York City is one of the biggest metropolitan cities and the most densely populated city in the United States. According to the U.S. Census Bureau, the big apple located in latitude 40.8 º and longitude -74 º, has a population of 19,541,453. Its weather statistics published by the U.S. Energy Department, a typical week during summer has an average temperature of 21.47°C, in winter 2.94°C, in fall 18.78°C, and in spring 6.54°C. (USDOE)

Radiation Level

According to NREL PVWatts Viewer, New York City receives an approximate solar radiation of 4.63 kWh/m²/yr, which in our study is categorized as level 2 (4 to 5 kWh/m²/yr). It has an average electricity rate of 13.22 cents/kWh but checking further, the current residential rate from ConEdison, the biggest energy supplier in the area and the referenced rate used in this study, it is 11.3 cents/kWh, which is rather higher than the average country rate for February 2011 which was 11.2 cents/kWh. (EIA 2011)

Incentives for Renewable Energy

According to U.S. Department of Energy, the state of New York through NYSERDA, offer incentives of $1.75/watt DC to a maximum of 12,250 and not exceeding 40% of the total cost of the system. In addition, the government offers, 100% sales tax exemption from the purchase of the system. The federal incentives consists of 2.2 cent/kWh with no restrictions in time (DSIRE 2011).

Figure 6. Collyer House

Historic Background and Precedents

Located in Chelsea, New York, Captain Moses W. Collyer House is a perfect example for a gambrel house following the Victorian style. Constructed in 1899, the structure was house of Moses Collyer, a river boat captain of the Hudson. The house is built out of wood framing on brick foundation with a gambrel roof out of shingles. (NYSOPRHP)

Construction Type

Traditional Gambrel roof trusses consisted of large frames at 4.5 to 6 meter centers. It contains in a series of roof joist and jointed with a nailed plywood gusset plate (Corkhill 1982).

Roof Type

Gambrel roofs are derivations of what is called a mansard roof which existed mostly in France to avoid taxation. According to Wikipedia, in 1783 a law from Paris restricted buildings to be built 65 feet high from the bottom floor to the cornice, allowing the mansard roof with steep sides and a double pitch, being exempt from this taxation and maximize the attic interior space for other uses.(Wikipedia)

2.2. Conch House: Miami, FL

Location

Located in the South East region of the United States Miami, is a densely populated city with 5,547,051 inhabitants in its metropolitan area (US.CensusBureau 2009) . Its climate is rather stable throughout the year. Located in latitude 27.5º and longitude -81.3º, Miami's average temperature is classified as tropical savanna and very hot/humid, therefore is has only 2 predominant periods: Dry and Wet Periods. During the wet period (May/June/July) the average temperature is 26.48°C and during the dry season (December/January/February) the average temperature is 20.53°C.(USDOE)

Radiation Level

According to NREL PVWatts, Miami has an average rate of 9.36 cents/kWh and an average radiation of 5.33 kWh/m²/yr, which falls into our category 3 (5 to 6 kWh/m²/yr). On the other hand, the main electric provider of the region, Florida Power and Light (FPL) rate for residential use is 8.77 cents/kWh, which is slightly lower than the average and the previously mentioned country's average rate of 11.2 cents/kWh on February 2011 (EIA 2011)

Historic Background and Precedents

The conch House Heritage Inn is located in the heart of old Key West and really close to Hemingway House Museum. The conch style is an architectural style only developed in the South Florida area and is attributed to influences of Bahamas immigrants but with some type of classical revival influence. It is considered vernacular architecture due to the utilization of materials acquired in the area like wood.(City of LakeWorth)

Figure 7. The Conch House Heritage Inn

<u>Construction Type</u>

Originally the earliest versions of conch houses were built like boats, using crossed braced timber frame methods but later replaced with balloon framing for economic reasons and faster construction. In balloon framing slender vertical studs extended from the sill to the roof plate, avoiding the heavy corner post with the previous method. Normally a 1 or 2 story structure, conch houses are set on wood post, limestone or concrete piers (Cammerer 1992).

Roof Type

Containing broad low pitched gabled and verandas as continuation of a roof slope in some cases, roofs in conch houses are made originally of wood shingles, but later evolving to pressed metal and composition shingles (City of LakeWorth).

Passive Strategies

Conch house are set on post and pier to allow air circulation under the house and use high sash windows, louvered windows, door shutters and high ceilings to allow the free circulation of natural ventilation inside and cool the house (City of LakeWorth).

Incentives for Renewable Energy

According to U.S. Department of Energy, the state of Florida offers a rebate of $4/watt DC up to $20,000 (in the system lifetime) for residences and a tax exemption of 100% from the purchase of the system. The federal incentives consists of 2.2 cent/kWh with no restrictions in time (DSIRE 2011).

2.2. Desert House: Phoenix, AZ

Location

Located in the South West corner of the United States and more especially in latitude 33.49 º and longitude -112.2 º, Phoenix has 1,445,632 inhabitants and has a subtropical arid climate (US.CensusBureau 2009). According to the Department of Energy, average temperature in Phoenix is 34.46°C during summer, 13.39°C during winter, 24.39°C during fall, and 22.75°C during Spring. It is located in the southern region of the Sonora Desert and at some point temperatures can reach up to 48.9°C (Weather.com). Phoenix is located at the Salt River Valley therefore its topography is rather flat, allowing the city for a precise grid organization. (Wikipedia)

Radiation Level

According to NREL PVWatts Viewer, radiation in the city of Phoenix is 6.18 kWh/m²/yr and an average radiation rate of 8.73 cents/kWh, but the largest electricity provider of the area is Arizona Public Service, which residential rate is 9.3 cents/kWh. Which is slightly lower than the national average mentioned previously which is 11.2 cents/kWh.

Historic Background and Precedents

A good precedent to take in consideration for this area is the desert house created for Jim Austin by Lloyd Russell. Consisting of a roof structure completely detached from the structure of the house that intends to receive of all the solar radiation from hitting directly to the rest of the livable spaces and reduce energy consumption . Additionally, there is also the very well known example of the desert home and is the Kaupmann House designed by architect Richard Neutra and located in Palm Springs, CA. Created in International Style, this house has the same concept of having a higher structure for protection as the previous example but just in some part of the house. Additionally, it has rows of movable vertical fins that offer protection from high solar radiation and sandstorms.(GreatBuildings). Other version of desert house example is La Luz Complex, designed by Architect Antoine Predock. It is a community of townhouses located in Albuquerque, NM, whose design emphasizes cul-de-sac streets or pedestrian hallways. In addition deep overhangs are created to prevent the sun from coming into the bigger glazed rooms or small windows are for the same purpose (Predock 2000).

Construction Type

Some desert houses are created out of massive adobe walls with local materials that operate as acoustical barrier and heat reservoir and some of these walls are stucco white to bounce the light into inner courtyards and prevent heat transfer. Normally this type of design uses a lot of pavers, clay roof tile and stones tiles produced locally. According to Antoine Predock's version of dessert houses "the thermal mass of the 12-in thick masonry walls absorbs the heat from the daytime sun and slowly radiates warth into the interior spaces in the cool of the evening" (Predock 2000). Normally some designs introduce excavated underground rooms to allow for thermal stability as well.

Figure 9. La Luz Complex by Antoine Predock

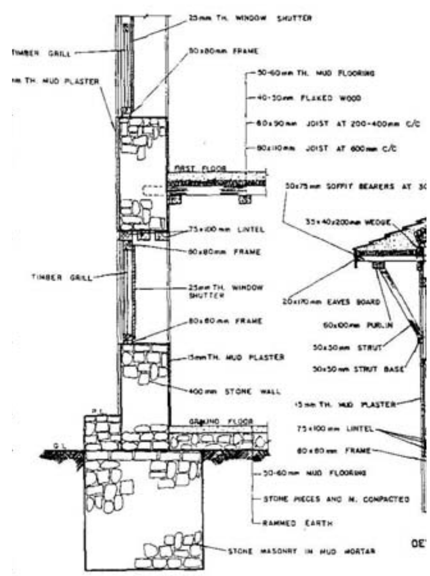


Figure 8. Desert House Construction

Roof Type

The roof in this type of house is flat and rigid since it's trying to acquire less solar radiation possible and since is an area with less probability of snowing the roof does not require any angle at all, thus reducing material needed for construction. Sometimes it uses the “cool roof technique” which consists of using a white or light coating of paint to reflect solar radiation and preventing the residence to heat up (Predock 2000).

Incentives for Renewable Energy

According to U.S. Department of Energy, the state of Arizona, offer incentives of \$1/Watt in up to 50% of total the project cost and up to a maximum of \$ 75,000 per project. In addition, the government offers, 100% sales tax exemption from the purchase of the system. The federal incentives consists of 2.2 cent/kWh with no restrictions in time. (DSIRE 2011)

CHAPTER 3

THE PHOTOVOLTAIC EFFECT

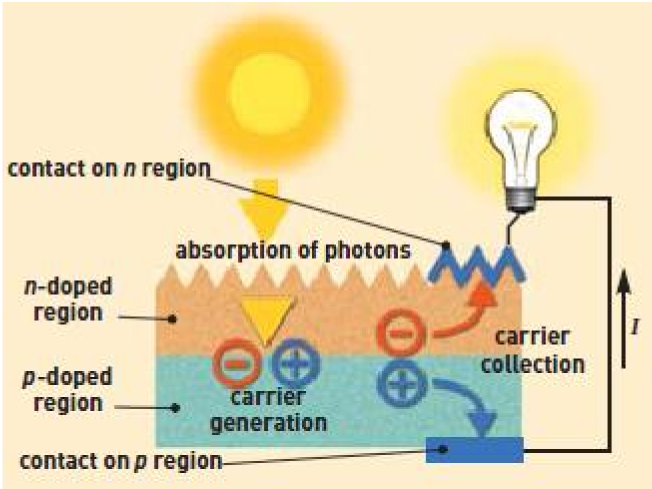


Figure 10. Photovoltaic Effect

In 1839, Edmund Becquerel discovered the photovoltaic effect, which consists of the physical phenomenon responsible for converting light into electricity. The way that this effect works is through a material that is a combination of two regions one with excess of electrons and the second with deficit of them (Becquerel 1839). According to the French department of atomic energy in its article "How Does Photovoltaic Cells Work?", the introduction of electricity through photons allows the movement of electrons thus creating an electric field within them and bring the electrons back to place. This movement creates a current that is driven out through other properties of the cell. (CEA)

The photovoltaic technology has gone through 3 different generations but even though there is strong research on second and third today, first generation is more marketable, better known and offers more possibilities to the regular home owner.

(1) Mono and Polycrystalline (Mono-Si) and Poly Silicon Crystalline (Poly-Si)

(2) Cadmium telluride (CdTe), and Copper Indium Gallium Selenide (CIGS)

(3) Amorphous Silicone (A-Si) and Organic (OPVC)

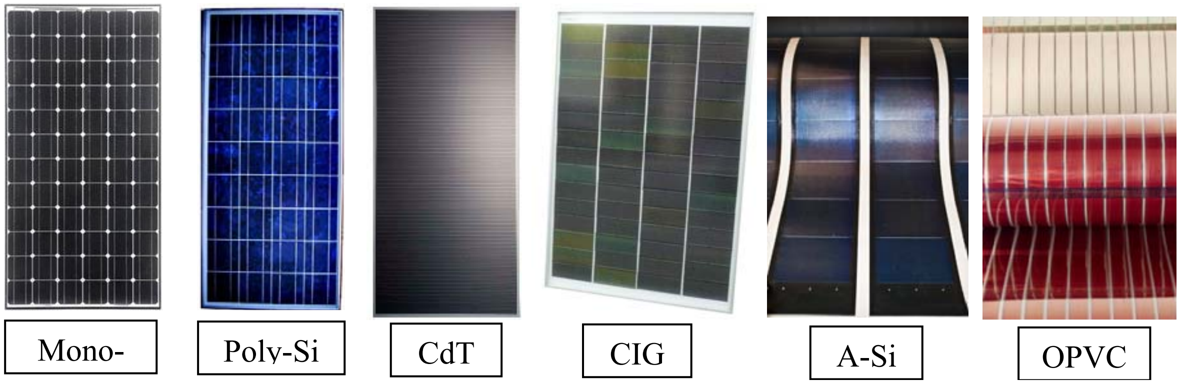


Figure 11. Photovoltaics available in the market

3.1. First Generation:

Currently first generation solar cells are the most widely used modules for energy harvesting around the world. According to NREL it is a technology that is expensive to build but with high efficiency in return, compared to Thin-Film (Second Generation) which has inexpensive manufacturing process but low efficiency (Heywang 2004).

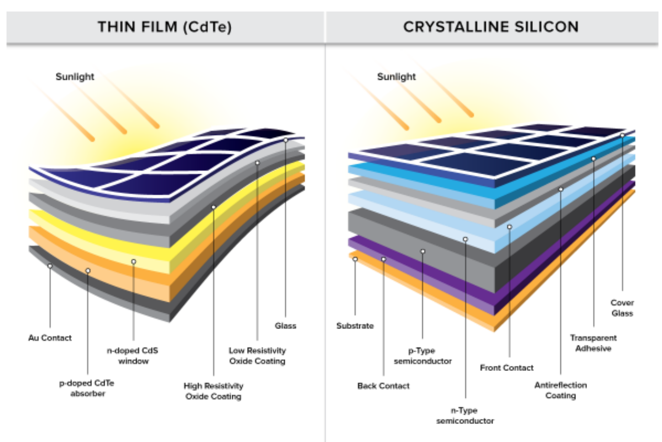


Figure 12. First and Second Generation of PV

Monocrystalline Silicon (Mono-Si).

It is a solar panel created using Czochralski process out of crystalline silicon which is the base material for all electronic industry (Wikipedia). Manufacturing of this solar cell is quite expensive and leads to a substantial amount of waste. According to NREL, Research done by Amonix shows an efficiency up to 27.6%.(NREL)

Polycrystalline Silicon (Poly-Si)

This solar cell is created in a similar way but is composed of a number of smaller crystals that are joined to form a large single "crystal". The efficiency of this solar cell is lower in comparison to Mono-Si, but is also cheaper to manufacture, therefore the most popular photovoltaic sold today (Heywang 2004). According to NREL, research done by FhG-ISE shows an efficiency of up to 20.4%.

3.2. Second Generation

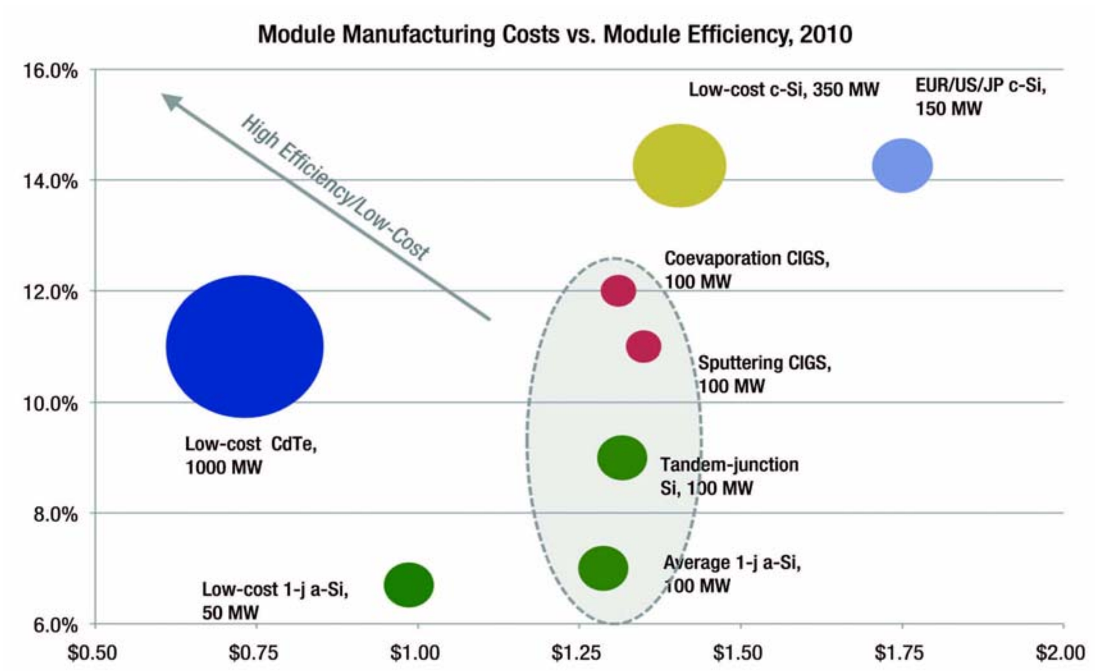


Figure 13. Expected future of Thin-film by GreenTechMedia (GTM)

This generation is currently under research, even though is now being used in only 20% of the projects around the world (GreenTechMedia). This technology promises a lot for the future if it can reach a higher efficiency at a lower production cost because of the utilization of thinner semiconductor layers and less utilization of material.

Cadmium telluride (CdTe)

Cadmium telluride is a crystalline compound toxic if is handled improperly. Solar cells of this component can reach an efficiency of around 16.7% based on research done by NREL but if the technology is fully developed, low availability of tellurium could be an issue.

Copper Indium Gallium Selenide (CIGS)

It is a solid solution that is a tetrahedrally bonded semiconductor. It is created through a vacuum base process or eletroplatting. According to NREL research on CIGS, it may have an efficiency of up to 20% to this date. Currently between 3-6% of the global market corresponds to CIGS.

3.3. Third Generation

This generation is the most recent version photovoltaics that are mostly being implemented in accessories of daily use or urban architecture. They have not been introduced into building structures because they are still under research but according to Martin A Green, they can potentially overcome the Shockley–Queisser limit of 31-41% efficiency. (Green 2001)

Amorphous Silicon (A-Si)

It is a solution that is not crystalline nor has the range of order normally present in other silicon. This technology suffers from low efficiencies and slow deposition rates leading to high capital costs, making it one of the least popular choices. However the biggest advantage of this option is that this solution only used 1% of the silicon used by crystalline solar cells, which is the main driver of the solar cells cost in today's market. Additionally, the material has flexibility which allow for the incorporation of these energy harvesting devices on complex curved architecture structures. According to NREL, Research done by United Solar shows an efficiency up to 12.5%

Organic (OPVC)

This type of solar cell is being research at a slower pace than the rest of the technologies (Konarka, Solarmer, Siemens, Plextronics, etc). It is the most recent acquisition but to the date, has not been greatly incorporated in architecture. Konarka offers PowerPlastics for solutions in urban architecture rather than residential and commercial uses. Like A-Si, OPVCs are flexible materials that uses conductive organic polymers or small organic molecules. In addition they may come in a wide range of colors and also can be translucent. However, they have low, efficiency, low power and low stability. According to NREL, Research done by Solarmer shows an efficiency up to 7.9% up to date. Figure 14 explains the different research done in all the technologies previously mentioned.

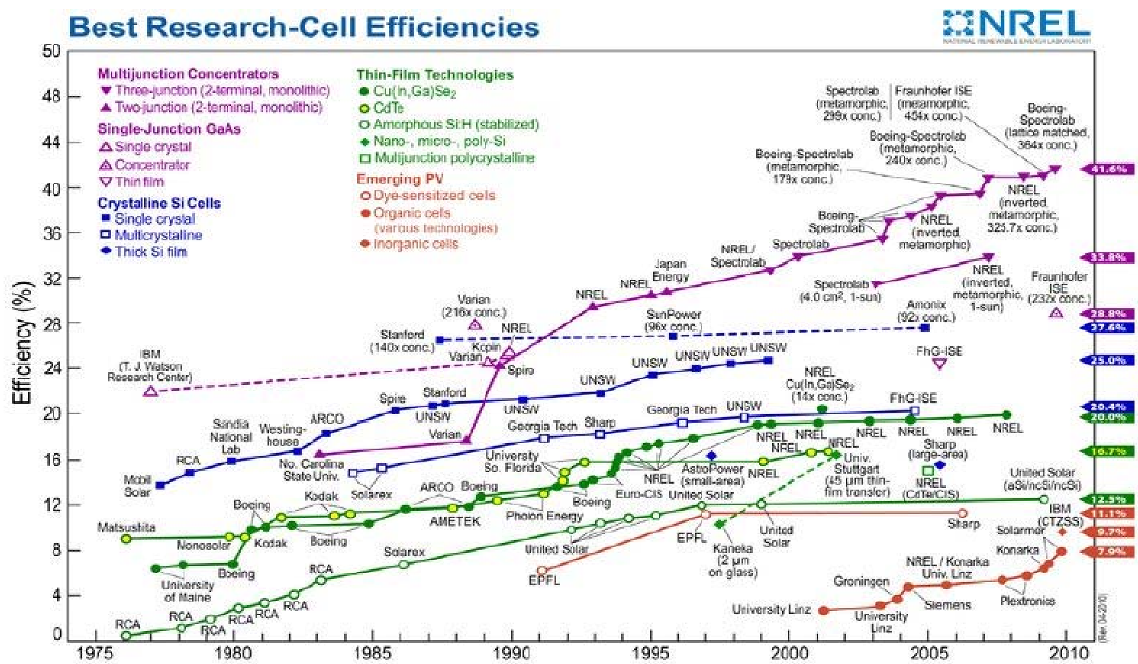


Figure 14. Best Research Cell Efficiencies by NREL

For the purpose of evaluating different geometries under reasonable conditions and traditional choices, the technology used for this study was chosen based on different conditions: The efficiency, affordability and availability of local american manufacturing firms (Mehta 2009). NREL list of most commercial Monocrystalline Silicone module of 2010 and Sanyo HIT-215NKHA5 (single crystal CZ Si, HIT (Tcoeff = -0.30 %/C),

V_{OC}/cell = 717 mV with efficiency of 17.1% was listed as second and therefore chosen for this task. The module is created by Sanyo, which is located in Salem, Oregon, just as shown on fig. 15 and it can be found in the ranges of $700 to $1500 per module (Roedern 2010). In addition, PVSyst is a software created by Energy Group from the University of Genova. The software was created for the study, sizing and simulation of photovoltaic systems at two stages: Preliminary and Project Design. It can be used by Architect, engineers and researchers at any type of construction and geometry. The costs introduced on the calculation for the payback period are based on this software which considers the cost of mounting supports between $0.85-1.43/kW, transport and mounting cost $2150/kW and inverter plus wiring between $860-1145/kW, which is more or less the same as the following percentages of the total cost as established by Manfred Bächler in his article “BOS Cost Savings" : Module Cost 73%, Inverter 7%, Substructure and installation 8%, (assuming is a non-ventilated system), DC Cabling 3%, Inverter 7%, Engineering 6%, and Other 3%. (Bächler). The cost of maintenance is based on NREL’s Fixed Operating & Maintenance Cost in 2007-2009 Study which says that the O&M for Solar panels is between $10-30/kW-yr, therefore this study assumes $20/kW-yr (NREL 2010).

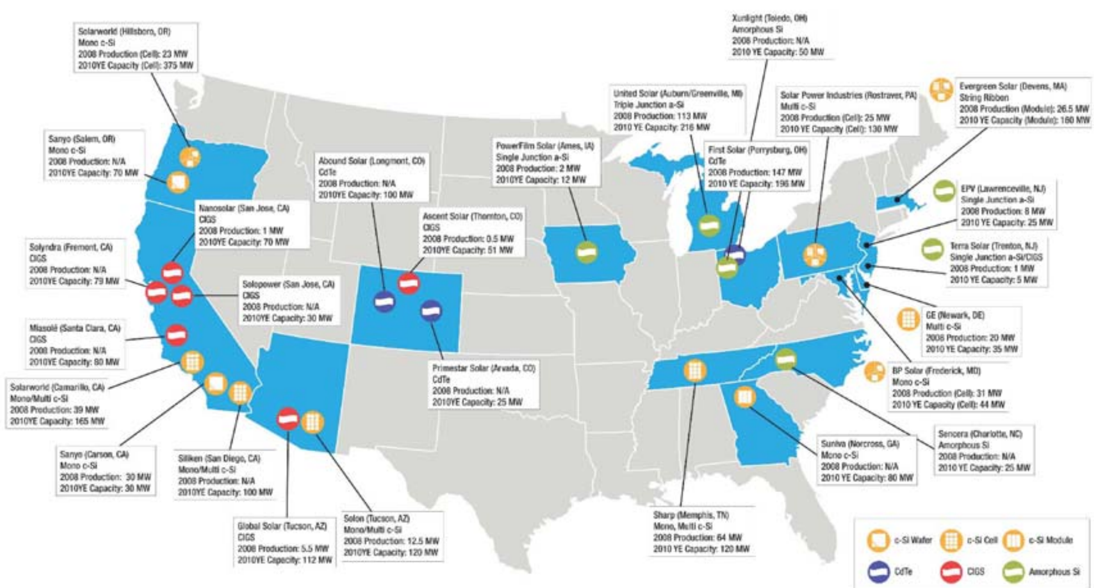


Figure 15. PV Manufacturing facilities in the U.S by GreenTechMedia (GTM)

CHAPTER 4

ANALYSIS: ENERGY PERFORMANCE VS. RETURN OF INVESTMENT COMPARISON.

The return of investment is a simple formula that according to Investopedia.com is a measurement to determine the efficiency of an investment over a period of time. A normal investment ranges in between 1 and 2, 0 showing no return at all but full payment of investment, 1 being a return of the same amount excluding investment cost and 2 being double return, lower than that is not a very encouraging investment, but higher than that is a very satisfying result (Investopedia 2011).

The following equation represents the formula that carries out this concept:

ROI = (Gain from Investment - Cost of Investment) / Cost of Investment

Assuming that the service life of a monocrystalline system is 20 years, the aim of the study is to achieve a return of investment higher than 1 as an achievable target for current market prices and incentives. The way that it was calculated was by adding the net income of each year including energy produced by PV system in dollars (keeping in mind inflation), energy saving by geometry or insulation improvements, incentives, reducing cost of material cost and maintenance, subtracting this by the cost of the investment and divide it by the same cost of investment. Table 1 shows the calculation made for a small seattle gable roof residence home as an example of this formula. Note that 42 modules were used because that is the amount able to fit on the roof of this design, also note that it has a ROI of 0.85 which is not the best under this conditions.

Table 1. Payback time and Return of investment calculation for Seattle Small Residence

PAYBACK ANALYSIS

INITIAL SYSTEM COST by PVSyst	Units	Price	Total
HIT Power 215N Solar Panel (Mono)	42	$ 769	$ 32,291
Neos 25 Inverter Eurener	1	$ 1,076	$ 1,076
Charge Controller	1	$ 538	$ 538
Support Cost	1	$ 5,920	$ 5,920
Wiring	1	$ 5,920	$ 5,920
Transport and Mounting	1	$ 8,073	$ 8,073
Initial System Cost Total			**$53,818**
U.S. Federal Tax Credit /year	$0.02	$ 258	
U.S. Federal Tax Credit Total (10 years)			**$2,577**
State Rebate/year (Limit 5000)	$0.30	$ 3,865	
State Rebate Total (9 Years)			$34,787
System Cost after Basic Credits			**$16,454**
Residential Energy Efficient Credit (state income tax)			
Total			**$16,454**

ANNUAL PRODUCTION	
Number of Panels	42
STC Rating in Watts Per Panel	215
Total Kilowatts per hour assuming optimum conditions	9
Estimated kilowatt hours per year	12,884
Electric rate (or sell back)	$0.06
Estimated Income (Year 1)	$760
Electrical Rate Annual Inflation Assumption	2.2%
Combined State and Federal Income Tax Bracket	10%

OPERATION AND MAINTENANCE (O&M) by NREL		
O&M	$20.00	kW/year
Annual	**$180.60**	

ENERGY SAVINGS (U1 vs U1)	
Electricity Typical Cost/ year (U1)	1719.416
Current Cost/year (U1)	1719.416
Difference	0
Gas Typical Cost/year (U1)	225.1012
Current Cost/year (U1)	225.1012
Difference	0
Total Energy Savings in Dollars	0

RETURN OF INVESTMENT 0.815163

ROI = Gain of Investment - Cost of Investment / Cost of Investment

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Relevant benefits																				
Energy Production	$760	$777	$794	$811	$829	$848	$866	$885	$905	$925	$945	$966	$987	$1,009	$1,031	$1,054	$1,077	$1,100	$1,125	$1,149
Energy Saving	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Incentives	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123	$ 4,123
Total benefits	$4,883	$4,900	$4,917	$4,934	$4,952	$4,970	$4,989	$5,008	$5,028	$5,048	$5,068	$5,089	$5,110	$5,132	$5,154	$5,177	$5,200	$5,223	$5,248	$5,272
Expected Rate of Rise in Energy Costs	2% (This would be ABOVE the rate of inflation)																			
Annual Net Costs for Improvements																				
Materials Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Maintenance	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181
Total costs	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181	$181
Net Income:	$4,702	$4,719	$4,736	$4,754	$4,772	$4,790	$4,809	$4,828	$4,847	$4,867	$4,887	$4,908	$4,929	$4,951	$4,973	$4,996	$5,019	$5,043	$5,067	$5,092
Initial Cost of Investment	$53,818																			
Net Cash Flow	($49,116)	$4,719	$4,736	$4,754	$4,772	$4,790	$4,809	$4,828	$4,847	$4,867	$4,887	$4,908	$4,929	$4,951	$4,973	$4,996	$5,019	$5,043	$5,067	$5,092
Cumulative Net Cash Flow	($49,116)	($44,396)	($39,660)	($34,906)	($30,135)	($25,345)	($20,536)	($15,709)	($10,862)	($5,995)	($1,108)	$3,801	$8,730	$13,681	$18,654	$23,650	$28,669	$33,712	$38,779	$43,871
Undiscounted payback period:	**11.41 Years**																			

By, having this calculation we can represent in different ways the effects of architectural articulation on the return for photovoltaic systems. These are some aspects:

4.1. All Possible Variations

The following inputs have been placed into the residential energy calculator created by Georgia Institute of Technology based on ISO Standard137790:2008 to rate the efficiency of each house according to their typical construction. For this study nine different variations of each typology were created (3 types of construction and 3 different sizes for all of them).

The three different sizes considered were the following:

(1) Small (Approx 171.8 m² = 1,849 ft² including 2 bedrooms, 2.5 bathrooms, kitchen, living room, dining and patio for two people)

(2) Medium (Approx 215 m² = 2,314 ft² including 4 bedrooms, 2.5 bathrooms, kitchen, living room, double garage, dining room and patio for four people)

(3) Large (Approx 294.2 m² = 3,166 ft² including 6 bedrooms, 3.5 bathrooms, kitchen, living room, triple garage, dining room and patio for six people).

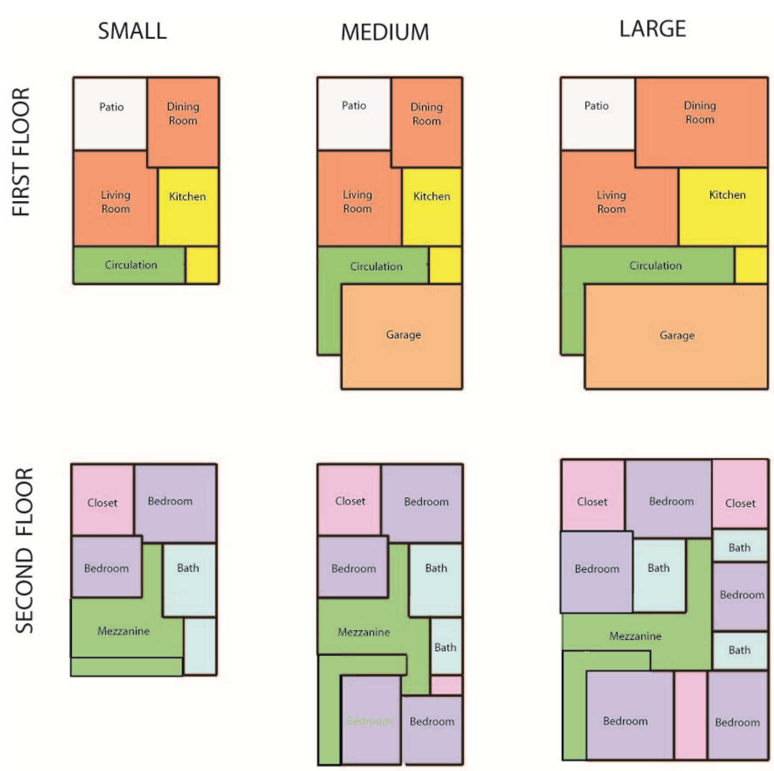


Figure 16. Architectural layout of each size of residence used for the study.

The three different type of construction considered were the following:

(1) Clay tile roof (U: 0.179 W/m²K, ε: 0.39), Brick wall (U: 0.283 W/m²K, ε: 0.92), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5)

(2) Metal Roof (U:0.227 W/m²K, ε: 0.462), Concrete Wall (U: 0.434 W/m²K, ε: 0.92), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5)

(3) Typical Construction of each Region:

- Seattle (Log Construction): Asphalt Shingles Roof (U:0.235 W/m²K, ε: 0.462), Log Wall (U:0.264 W/m²K, ε: 0.91), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5)

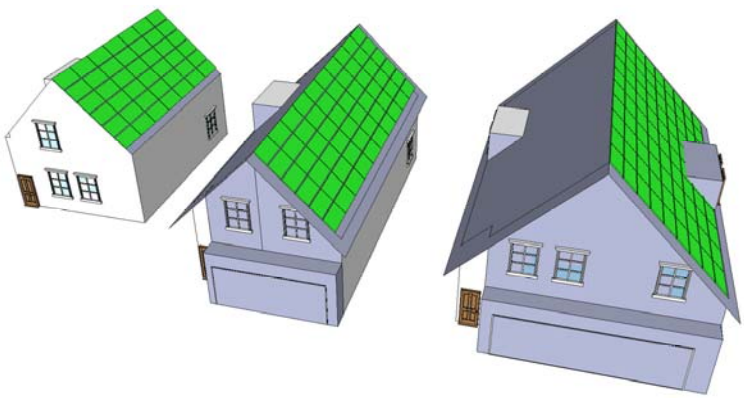


Figure 17. Gable Roof Houses designed for different occupancy requirements.

- New York (Gambrel Construction): Asphalt Shingles Roof (U:0.235 W/m²K, ε: 0.462), Wood Framed Walls with weatherboard (U: 0.37 W/m²K, SHGC: 0.85), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5).

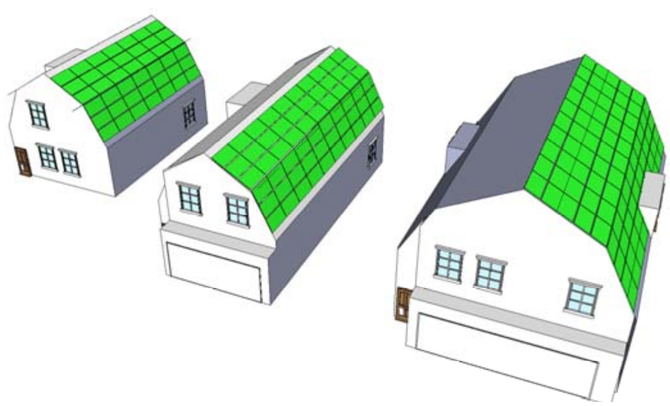


Figure 18. Gambler Roof Houses designed for different occupancy requirements

- Miami (Conch Construction): Wood shingle roof (U: 0.231 W/m²K, SHGC: 0.462), Wood Framed Walls with weatherboard (U: 0.37 W/m²K, SHGC: 0.85), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5).

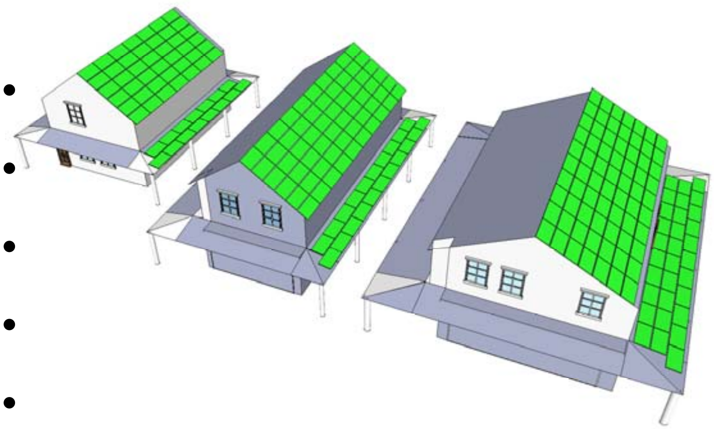


Figure 19. Conch Houses designed for different occupancy requirements

- Phoenix (Desert Construction): Membrane sheathing roof (U: 0.206 W/m²K, SHGC: 0.46), Stone Wall with Stucco (U: 1.5 W/m²K, SHGC: 0.90), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5).

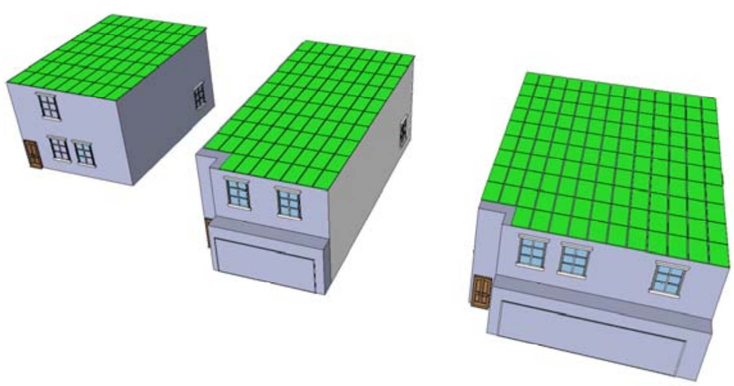


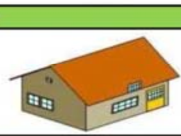
Figure 20. Desert Houses designed for different occupancy requirements

The following table represents the total set of inputs incorporated in each calculator to compare the actual energy efficiencies of these specific cases with the most common conditions for the region, starting from electricity and gas supplier to sales tax.

Table 2. Parameters used in the different typologies for this study

Location												
City	Seattle, WA			New York City, NY			Miami, FL			Phoenix, AZ		
Radiation	2.5 to 4 kWh/m2/year			4 to 5 kWh/m2/year			5 to 6 kWh/m2/year			6 and Up kWh/m2/year		
Type of Construction	**LOG HOUSE:**			**GAMBREL HOUSE**			**CONCH HOUSE**			**DESERT HOUSE**		
												
Classification	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
	2 Bed	4 Bed	6 Bed	2 Bed	4 Bed	6 Bed	2 Bed	4 Bed	6 Bed	2 Bed	4 Bed	6 Bed
General Building Information												
Total area for Living Room + Kitchen	37	37	50.4	37	37	50.4	37	37	50.4	37	37	50.4
Total area for other conditioned space	134.8	178	243.8	134.8	178	243.8	134.8	178	243.8	134.8	178	243.8
Total floor area for dwelling [m^2]	171.8	215	294.2	171.8	215	294.2	171.8	215	294.2	171.8	215	294.2
Area for other air-cond. public space	0	0	0	0	0	0	0	0	0	0	0	0
Total building gross area [m^2]	171.8	215	294.2	171.8	215	294.2	171.8	215	294.2	171.8	215	294.2
Total volume for air-conditioned space	550.18	787.18	1274.3	554.41	783.2	1400	523.2	756	1081.4	615	842.7	1221
Internal Temperature Set Point												
Internal set point for cooling [°C]	24.0											
Internal set point for heating [°C]	21.0											
Material												
Roof U-value [W/(m^{2}K)]	0.235	0.179	0.227	0.235	0.179	0.227	0.231	0.179	0.227	0.206	0.179	0.227
Roof - Emissivity	0.462	0.39	0.462	0.462	0.39	0.462	0.462	0.39	0.462	0.46	0.39	0.462
Opaque Wall U-value [W/(m^{2}K)]	0.264	0.283	0.434	0.37	0.283	0.434	0.37	0.283	0.434	1.5	0.283	0.434
Opaque Wall Emissivity	0.91	0.92	0.92	0.85	0.92	0.92	0.85	0.92	0.92	0.9	0.92	0.92
Window Type 1 U-value [W/(m^{2}K)]	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Window Type 1 Solar Transmittance	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Window Type 2 U-value [W/(m^{2}K)]	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Window Type 2 Solar Transmittance	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Door material U-value [W/(m^{2}K)]	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Envelope Heat Capacity (J/(Km2))	H	M	VH	H	M	VH	H	M	VH	H	M	VH
Building System												
Ventilation												
Mechanical ventilation fan	None											
Mechanical ventilation fresh air flow rate	43	60	90	43	60	90	43	60	90	43	60	90
Exhaust air recirculation percentage	None											
Heat recovery type	None											
Infiltration and air leakage level	Mechanical: Normal											
Cooling & Heating												
Cooling System Energy Efficiency Ratio	2.70											
Heating System Overall Efficiency	0.85											
Pump control for cooling	No pump for cooling											
Pump control for heating	No pump for heating											
Lighting												
Installed peak lighting power intensity	6.0											
Lighting control factor	Manual											
Domestic Hot Water												
DHW generation system type	Electricity											
DHW distribution system type	Tap more than 3 m from heat generation											
Energy Generation System												
Solar Photovoltaic												
PV module Surface Area (m^2)	77.29	105.33	147.25	33.83 / 34.3	44.5 / 50	61 / 66.6	58.1 / 28	76.4 / 37.9	98.03 / 53.1	85.95	121.23	173.06
Orientation and Tilt Angle	45			60 / 45	60 / 45	60 / 45	45 / 0	45 / 0	45 / 0	0		
Type of PV module	Monocrystalline Silicone											
Type of building integration of PV mod	Unventilated modules											
Solar Thermal												
Solar Collector Surface (m^2)	None											
Orientation and Angle	None											
Energy Carriers												
Primary energy source for ELECTRIC	Electricity											
Primary energy source for HEATING												
Primary energy source for DHW												

Energy Source Cost Rates (Only specify selected sources)				
Electricity Purchase				
Supplier	PacifiCorp	ConEdison	Florida Power & Light	Arizona Public Service
Usage Cost ($/kWh)	0.059	0.113	0.0877	0.093
Sales Tax (%)	9.5%	8.38%	7.0%	9.3%
Other Fees ($/Month)	6	0	0	0
Electricity Sell				
price per kWh ($/kWh)	0.120	0	0	$0.04
Natural Gas				
Supplier	Puget Sound Energy	ConEdison	Florida City Gas	SouthWest Gas Corp.
Price per Therm ($/Therm)	0.70177	0.7859	0.56213	0.64473
Sales Tax	9.5%	8.38%	7.0%	9.3%
Base and Service Charge ($/month)	10	16.8	8	10.7
Fuel Oil				
Price per Therm	N/A	N/A	N/A	N/A
Sales Tax				
Base and Service Charge				

Envelope Area	Orientation	Opaque	Door	Win1	SCF*	Win2	SCF*	Opaque	Door	Win1	SCF*	Win2	SCF*	Opaq	Door	Win1	SCF*	Win2	SCF*	Opaq	Door	Win1	SCF*	Win2	SCF*
Small																									
	S	47.5		1.5	1			38.5		1.5	1			61.1		1.5	0.5			47.5		1.5	1		
	E	37.4		12.0	1			38.7		12.0	1			41.0		12.0	0.58			37.4		12.0	1		
	N	49.4		3.0	1	1.8	1	42.9		3.0	1	1.8	1	58.6		3.0	0.66	1.8	1	49.4		3.0	1	1.8	1
	W	43.2	1.7	4.5	1			44.5	1.7	4.5	1			46.7	1.7	4.5	0.58			43.2	1.7	4.5	1		
	Hor	85.9			1			85.9			1			85.9			1			85.9			1		
Medium																									
	S	67.5		1.5	1			56.9		1.5	1			85.8		1.5	0.5			67.5		1.5	1		
	E	38.5		12.2	1			36.8		12.2	1			40.8		12.2	0.58			38.5		12.2	1		
	N	72.5		4.5	1	1.8	1	61.9		4.5	1	1.8	1	83.0		4.5	0.66	1.8		72.5		4.5	1	1.8	1
	W	31.8	14.5	3.0	1			31.5	14.5	3.0	1			35.5	14.5	3.0	0.58			31.8	14.5	3.0	1		
	Hor	127.2						127.2			1			127.2			1			127.2			1		
Large																									
	S	66.2		3.3	1			76.8		3.3	1			80.7		3.3	0.5			66.2		3.3	1		
	E	61.7		18.0	1			68.9		18.0	1			57.2		18.0	0.58			61.7		18.0	1		
	N	64.5		4.5	1	1.8	1	76.5		4.5	1	1.8	1	73.9		4.5	0.66	1.8		64.5		4.5	1	1.8	1
	W	60.9	18.8	4.5	1			63.1	18.8	4.5	1			81.7	18.8	4.5	0.58			60.9	18.8	4.5	1		
	Hor	182.1			1			182.1			1			182.1			1			182.1			1		

EPC				
Energy Delivery Performance Reference	122.39	190.22	101.26	115.77
Incentives				
State	$0.30/kWh (production) Up to $5000/year	$1.75/watt DC; Incentive may be reduced for potential production losses associated with shading, system orientation, tilt angle, and other factors. Up to $12,250	$4/watt DC Up to $20,000	$1.00/watt DC, adjusted based on expected performance. Up to 50% of project costs.
Federal	2.2¢/kWh for 10 years. 30% of personal tax credit			

When putting together all the information, the calculator gives the results presented on table 3. Keep in mind that the Return of Investment (ROI) shown in several occasions are negative because it is based on the lifetime of the solar panels which according to Sanyo guarantee lifetime of the chosen module is 20 years (Sanyo 2010). This suggests that at the moment the investment in photovoltaics under these conditions is not feasible. According to NREL’S Study of Simple Payback for photovoltaic system (with and without incentives) only a few states are able to have a payback time between 0 to 10 years, including Arizona, California, New Mexico and Nevada but it depends on the specific conditions of the project . For example only residences or commercial construction connected to Tucson Electric Power with renewable energy incentives of $2.00/W with an only limit of not exceeding 60% of the project cost may achieve a higher ROI.

Table 3. Return of Investment, Paybacktime and Energy Performance for all the typologies under actual conditions.

		Seattle [Typical]	Seattle [Clay tile roof & Brick wall]	Seattle [Metal roof & Concrete Wall]	New York [Typical]	New York [Clay tile roof & Brick wall]	New York [Metal roof & Concrete Wall]	Miami [Typical]	Miami [Clay tile roof & Brick wall]	Miami [Metal roof & Concrete Wall]	Phoenix [Typical]	Phoenix [Clay tile roof & Brick wall]	Phoenix [Metal roof & Concrete Wall]
SMALL	[E.1] Energy Need												
	$Q_{design,nd}$ [$kWh/m^2/yr$]	154	156	163	137	132	139	140	137	142	242	159	168
	Q_{ref_nd} [$kWh/m^2/yr$]	151											
	EPCnd	1.02	1.03	1.08	0.90	0.88	0.92	0.93	0.91	0.94	1.60	1.05	1.11
	Payback Years (Incent)	14.34	14.48	14.93	32.77	30.13	34.23	37.74	37.33	37.96	35.92	25.76	18.83
	ROI Incentives	0.56	0.54	0.47	0.01	0.08	-0.03	-0.10	-0.09	-0.10	-0.07	0.24	0.64
	Payback Years	113.04	122.63	164.52	49.96	45.16	52.68	62.03	61.20	62.49	53.01	35.61	25.63
	ROI	-0.66	-0.68	-0.75	-0.28	-0.21	-0.32	-0.10	-0.41	-0.10	-0.32	-0.01	0.36
MEDIUM	[E.1] Energy Need												
	$Q_{design,nd}$ [$kWh/m^2/yr$]	147	161	181	147	144	149	91	88	92	243	160	167
	Q_{ref_nd} [$kWh/m^2/yr$]	151											
	EPCnd	0.98	1.06	1.20	0.98	0.95	0.99	0.60	0.58	0.61	1.61	1.06	1.11
	Payback Years (Incent)	14.57	14.78	15.28	42.46	39.63	46.32	43.69	43.37	43.94	40.81	29.82	30.28
	ROI Incentives	0.53	0.50	0.43	-0.19	-0.14	-0.48	-0.20	-0.20	-0.21	-0.16	0.10	0.08
	Payback Years	116.56	131.75	186.21	63.37	58.09	70.87	68.02	67.38	68.52	58.96	61.59	63.28
	ROI	-0.67	-0.70	0.43	-0.42	-0.14	-0.48	-0.46	-0.20	-0.47	-0.39	-0.41	-0.43
LARGE	[E.1] Energy Need												
	$Q_{design,nd}$ [$kWh/m^2/yr$]	156	170	175	146	153	149	92	89	93	230	161	167
	Q_{ref_nd} [$kWh/m^2/yr$]	151											
	EPCnd	1.03	1.12	1.16	0.97	1.01	0.99	0.61	0.59	0.61	1.52	1.06	1.10
	Payback Years (Incent)	13.58	14.33	14.66	35.63	39.49	37.63	41.32	46.34	41.32	33.64	18.67	18.83
	ROI Incentives	0.65	0.52	0.46	-0.06	-0.14	-0.10	-0.18	-0.26	-0.18	-0.02	0.65	0.64
	Payback Years	111.23	196.50	284.19	48.94	55.55	52.33	61.32	71.19	61.32	51.09	25.38	25.63
	ROI	-0.65	-0.78	-0.83	-0.26	-0.14	-0.31	-0.41	-0.26	-0.18	-0.29	0.38	0.36

- Typical Construction in the Area
- Results with incentives
- Results under normal conditions
- Energy Performance Calculator

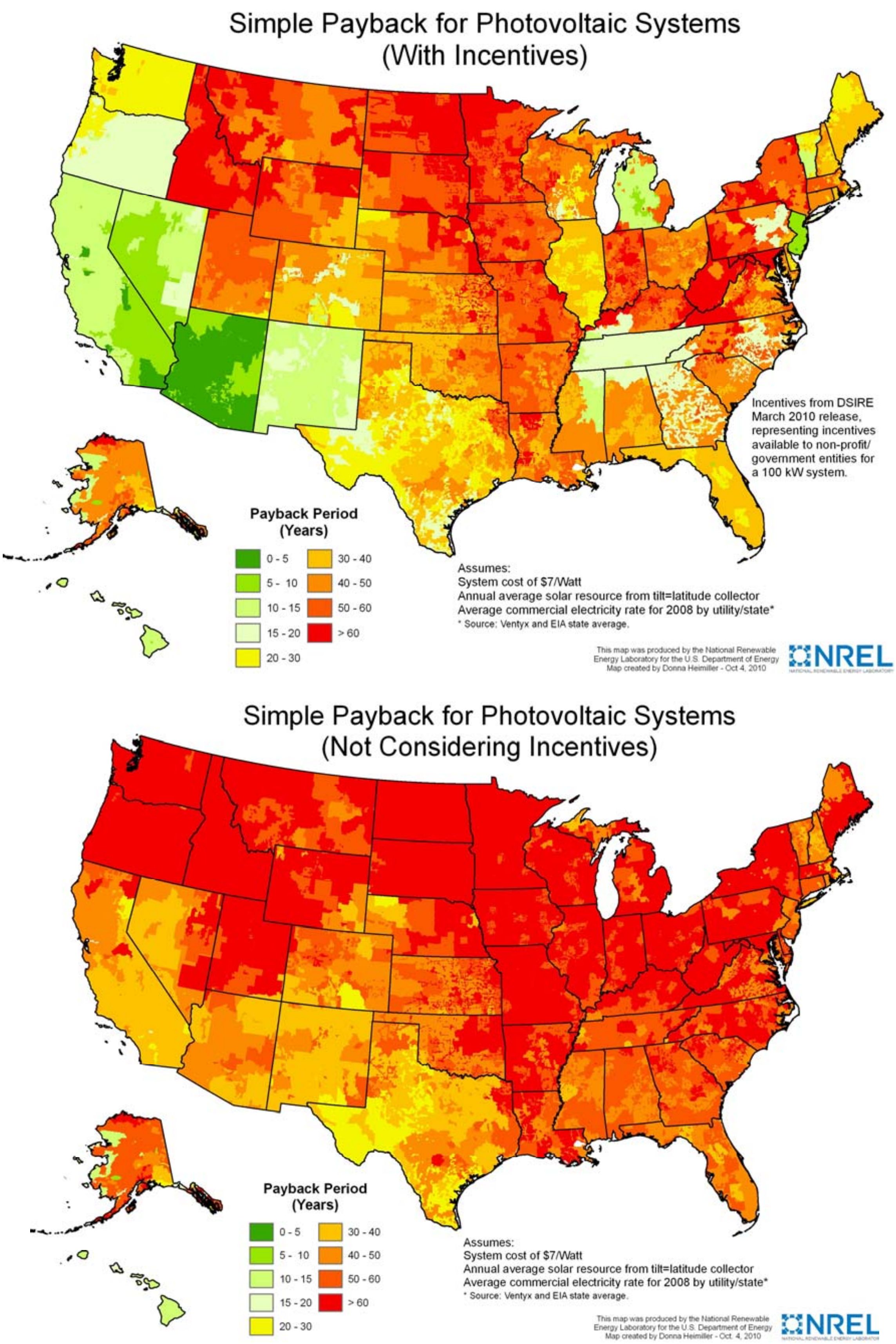


Figure 21. Simple Payback in the U.S by NREL.

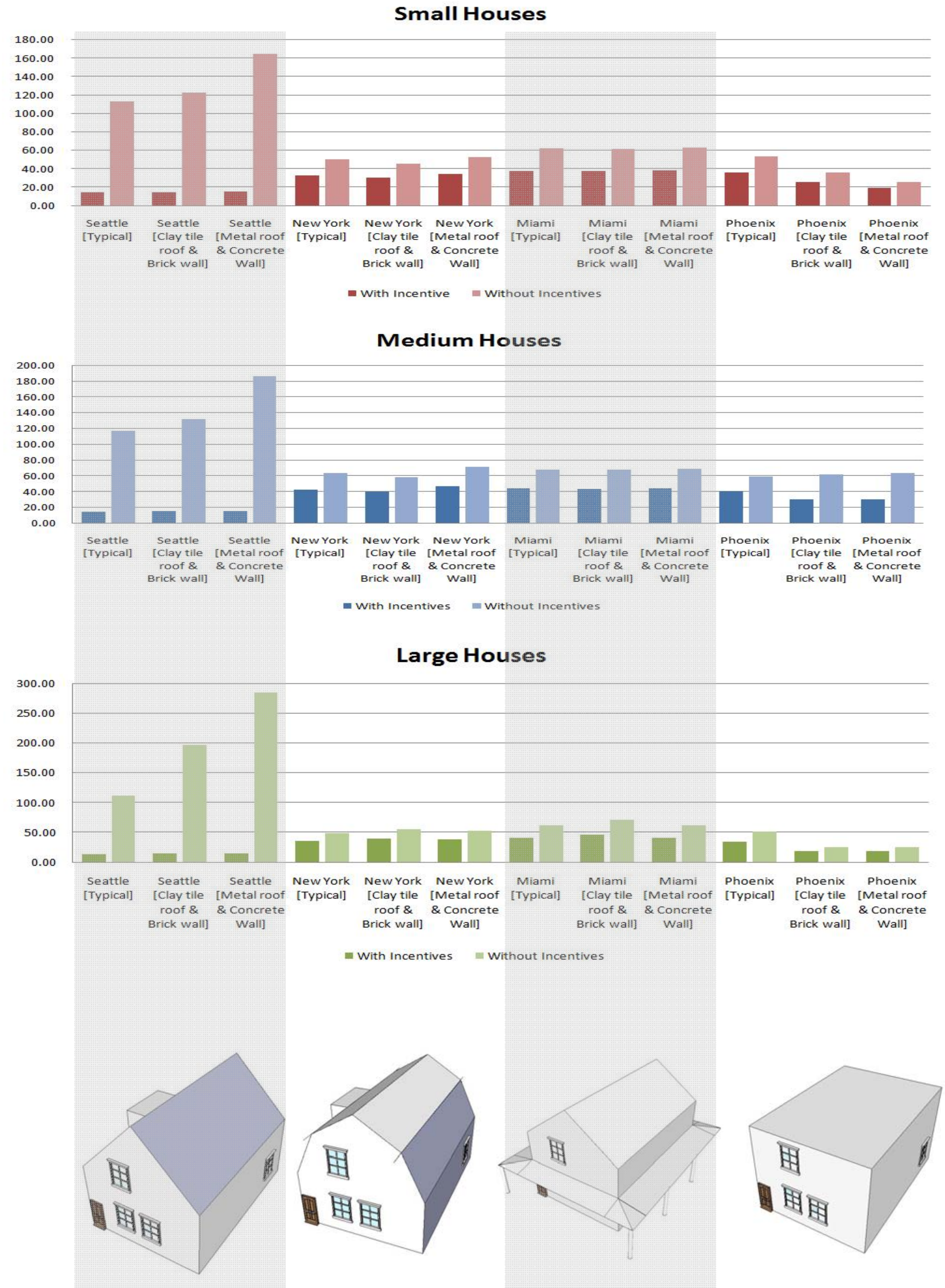


Figure 22. Comparison of payback time (years) in typologies under actual conditions (with and without incentives)

Therefore every individual case do not resemble the overall study shown by this map but just a general overview of all cases and all incentives. However do note on the map for simple payback with no incentives that the areas of higher radiation level are the ones that come closer to more reasonable payback time therefore the location is a major driver for the energy production, and this is going to be explored later on 4.10 Location Variation section. In conclusion, incentives are very relative to the conditions in which the design is under but the level of radiation may enhance or minimize these results.

By introducing the actual conditions of one particular design in the different regions, the study shows out of the designs explored, Seattle Log House design is the one that has more possibilities of giving a reasonable amount of time in payback for all three house sizes (around 14-15 years in payback) and as seen on the map of simple payback for photovoltaic systems with incentives Seattle comes forth in the 20-30 years payback time category , since the state gives incentives based on performance annually rather than an initial total incentive like in the other regions, the energy cost is relatively low and the efficiency of the panels increase due to the angle of the roof. However, for the rest of the regions, monocrystalline silicon is still affordable but certain conditions like energy supplier as mentioned before, are very important to have a better accessibility to higher incentives. In addition, conditions specified for the desert house, seems to approach that range of 15-30 years as well since it is the typology that uses more roof area and has the higher level of radiation out of the examples. Figure 22 is the representation of payback years for the different conditions earlier described.

4.2. GeometryVariation with different active (PV) areas in Small Houses

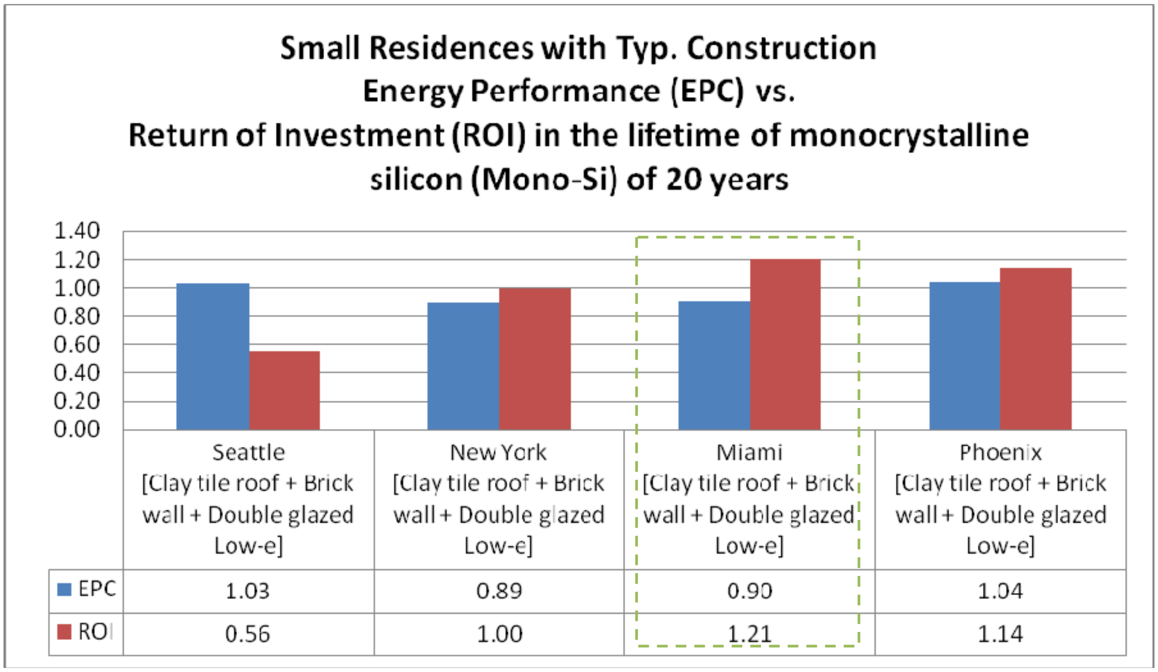


Figure 23. Geometry Alteration in Small Houses

Table 4. Payback and Energy Performance for different size of houses with same construction at different solar radiation levels.

		Seattle [Clay tile roof + Brick wall + Double glazed Low-e]	New York [Clay tile roof + Brick wall + Double glazed Low-e]	Miami [Clay tile roof + Brick wall + Double glazed Low-e]	Phoenix [Clay tile roof + Brick wall + Double glazed Low-e]
SMALL	[E.1] Energy Need				
	EPCnd	1.03	0.89	0.90	1.04
	Payback Years (Incentives)	11.41	11.24	10.17	10.40
	ROI Incentives	0.56	0.84	1.21	0.99
	Payback Years	113.04	57.78	78.29	79.12
	ROI	-0.66	-0.54	-0.57	-0.68
MEDIUM	[E.1] Energy Need				
	EPCnd	0.72	0.92	0.58	1.05
	Payback Years (Incentives)	11.98	11.55	12.44	10.15
	ROI Incentives	0.73	0.79	0.66	1.04
	Payback Years	96.04	91.65	100.78	78.15
	ROI	-0.73	-0.72	-0.75	-0.68
LARGE	[E.1] Energy Need				
	EPCnd	0.76	0.93	0.58	1.05
	Payback Years (Incentives)	12.89	12.93	10.30	10.35
	ROI Incentives	0.61	0.60	1.01	1.00
	Payback Years	105.53	105.99	79.56	80.03
	ROI	-0.76	-0.76	-0.68	-0.68

When evaluating the four different typologies with the same set of parameters like incentives (for this evaluation federal incentive of 2.2 cents/kWh and state incentive of 30cents/kWh were chosen), insulation and energy rates, the different geometries seem to differ on the Return of Investment as well due to their advantages and disadvantages created by the architectural articulation of the house. For example, we can see that with typical construction Seattle, New York and Miami residences are rather similar in terms of Energy Performance Calculation of energy demand (EPC) and Return on Investment Index (ROI). Phoenix residence on the other hand, portraits a high EPC due to low insulation and a low ROI because out of the 4 typologies is the one that has the possibilities of incorporating more solar panels in its plane horizontal roof (63 panels in this case) having a total initial cost of $84,028 compared to $59,687 from New York Gambrel House and Seattle Log House, and $79,448 from Miami Conch House but the efficiency decreases due to its position. Thus generation energy differs, out of all the typologies, the Desert house is the one that has more energy generation throughout the whole year (21,420 kWh/year) but at the same time high EPC value, thus even though the initial cost of 63 modules system is quite similar to Miami Conch House, the Return of Investment Index (ROI) is quite similar as well. The reason for the higher generation of electricity between the desert house and conch house differs on the ftilt variable (factor of correction) that is 1 for the desert home while, 1.09 for the conch residence and which is based on the geometry of the roof and reflects the efficiency of the panels placed a certain degrees. However, this evaluation shows that at least for smaller houses, the more radiation acquire the higher ROI.

4.3. Geometry Variation with different active (PV) areas in Medium Houses

On the other hand medium residences reflect different results, keep in mind that the alteration of the house to become a medium size was not made proportional but instead to fit the requirements of the inhabitable space for 4 people rather than 2 of the small version in the simplest form of the typology. The design was created to have a real understanding of the behaviour in actual cases. Phoenix and New York seem to be quite profitable with their results achieving 0.92 and 1.04 in return of investment due to the availability of area for solar panels and the possible inflation energy cost increase of 2.2% as presented by the U.S. Energy Information Administration (EIA) on its its Short-term energy Outlook presented on June7th, 2007.

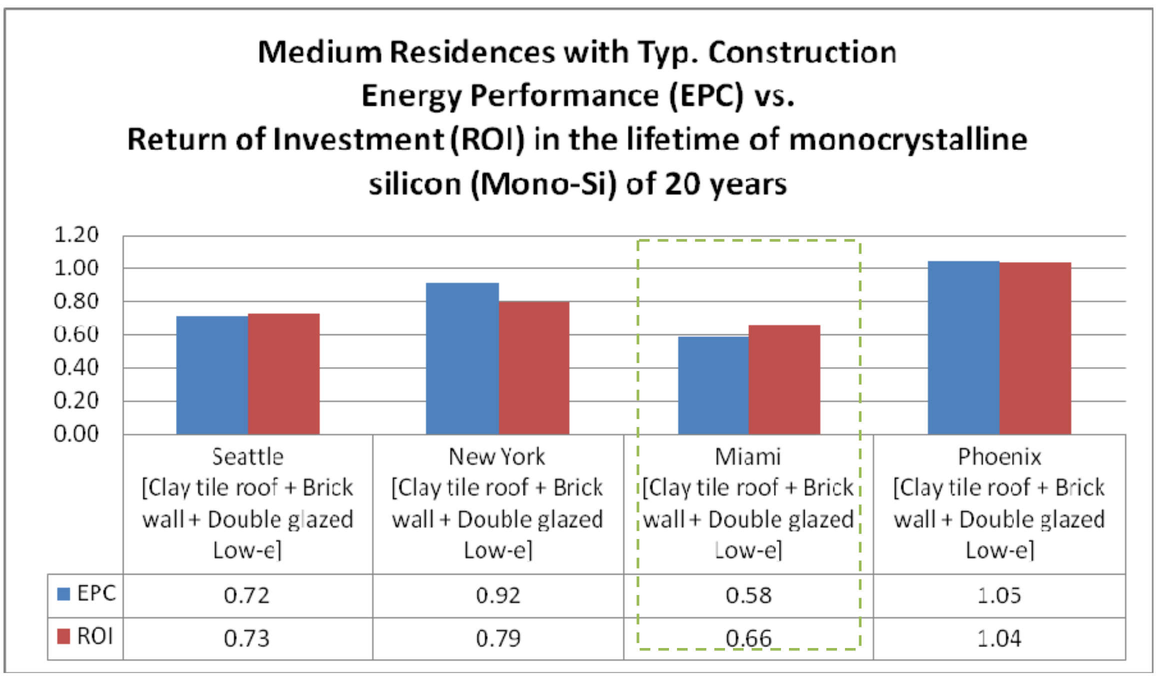


Figure 24 Geometry Alteration in Medium Houses

4.4. Geometry Alteration with different active areas in Large Houses

Additionally, I tried to evaluate the typologies in the larger size, giving again a very variable result between performance and payback but Miami once again seem to be the most favorable return for this type of insulation with a low energy performance calculation (energy requirement) .

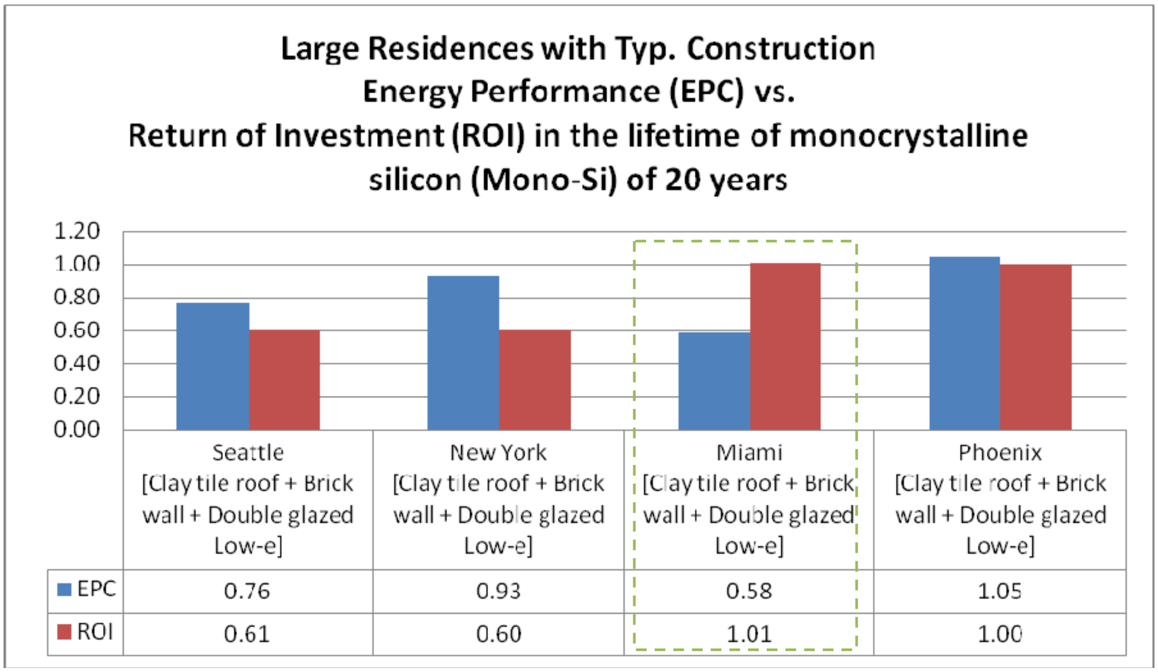


Figure 25 Geometry Alteration in Large Houses

4.5. Proportional sizing in one typology

Therefore, it was decided to evaluate a typology (Seattle Gable Roof Home) sized up in proportional scale rather than by design interior requirements which should declare more stable results for this purpose.

As shown in this graph the Energy Performance Coefficient (EPC) rises drastically as the residences gets bigger and the Return of Investment (ROI) is rather stable or slowly gets lower but tries to go back up in this case due to climate conditions. It seems that the overall cost of the system in this case depends much more on the active area available of the roof than the interior performance of the house, because there is no insulation changes between these examples, the construction technique is the same and the only changes on the EPC are caused by occupancy, and solar radiation.

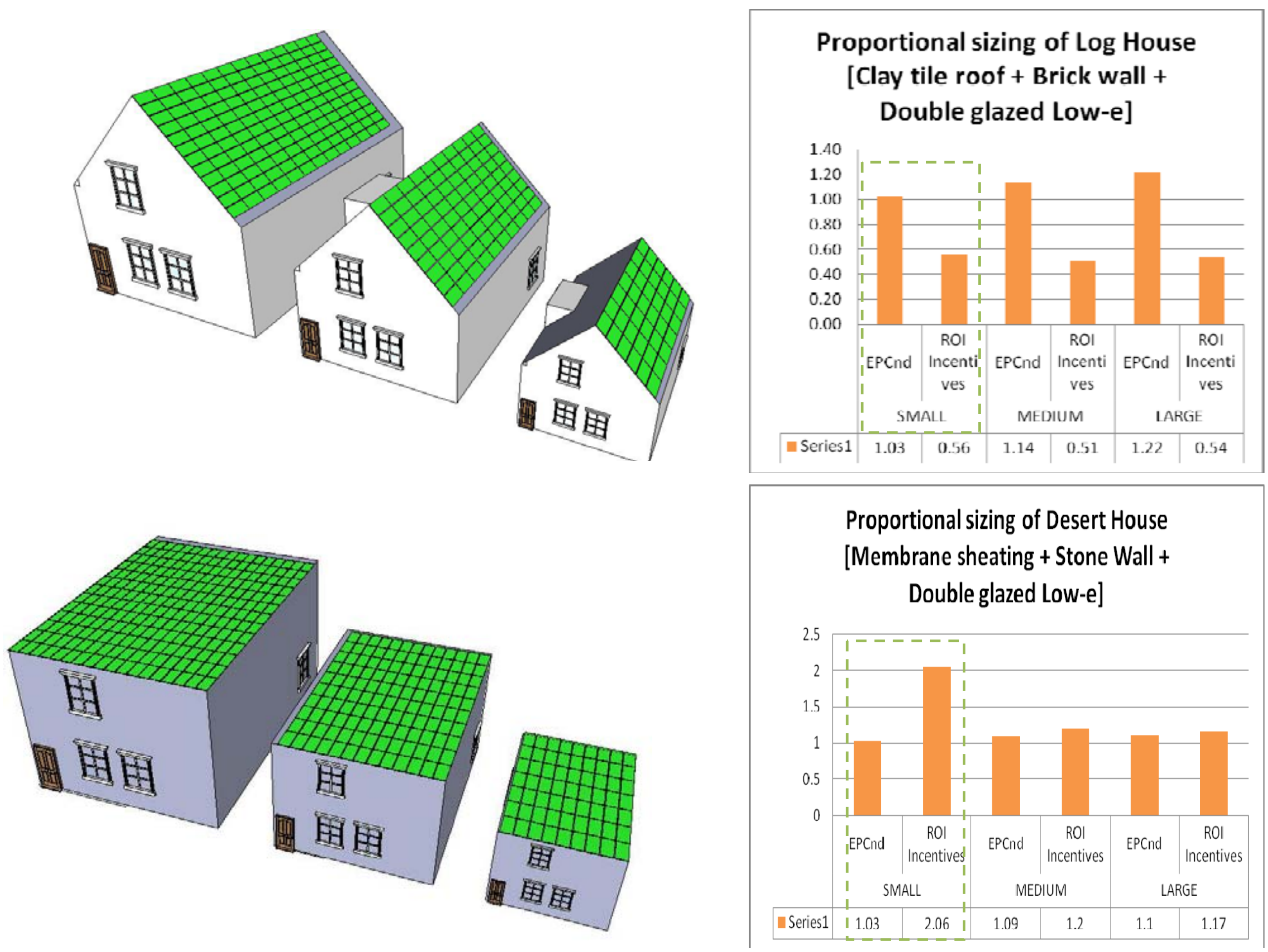


Figure 26 Proportional sizing of a typology

4.6. Insulation Variation

However, on the other hand, I compared variations of the same house, not in terms of size but in terms of insulation and construction methods, by introducing the following U values under the Seattle Log House and Desert House design:

- Typical Seattle (Log Construction): Asphalt Shingles Roof (U:0.235 W/m²K, ε: 0.462), Log Wall (U:0.264 W/m²K, ε: 0.91), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5)
- Typical Phoenix (Desert Construction): Membrane sheathing roof (U: 0.206 W/m²K, SHGC: 0.46), Stone Wall with Stucco (U: 1.5 W/m²K, SHGC: 0.90), Double Glazed

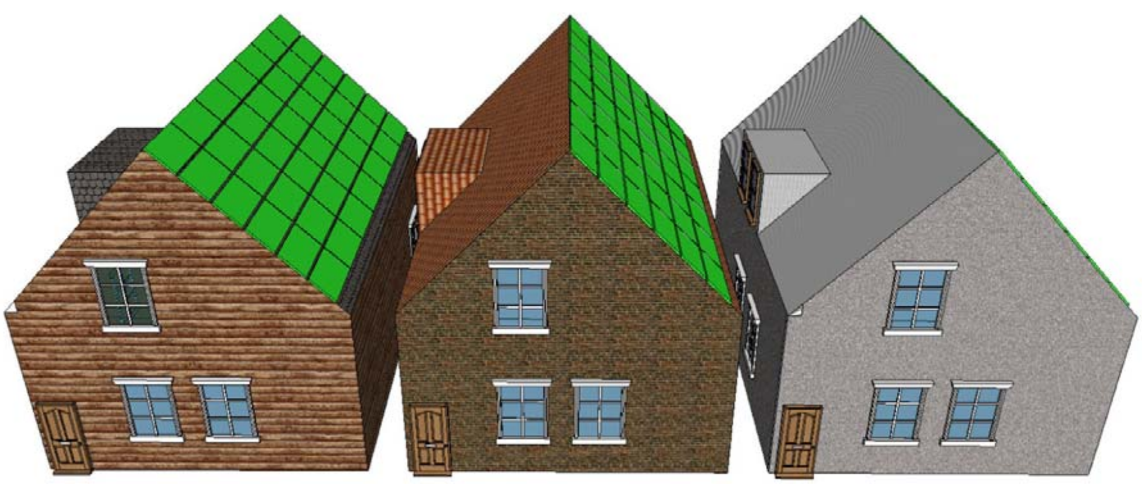


Figure 27 Same typology different insulation

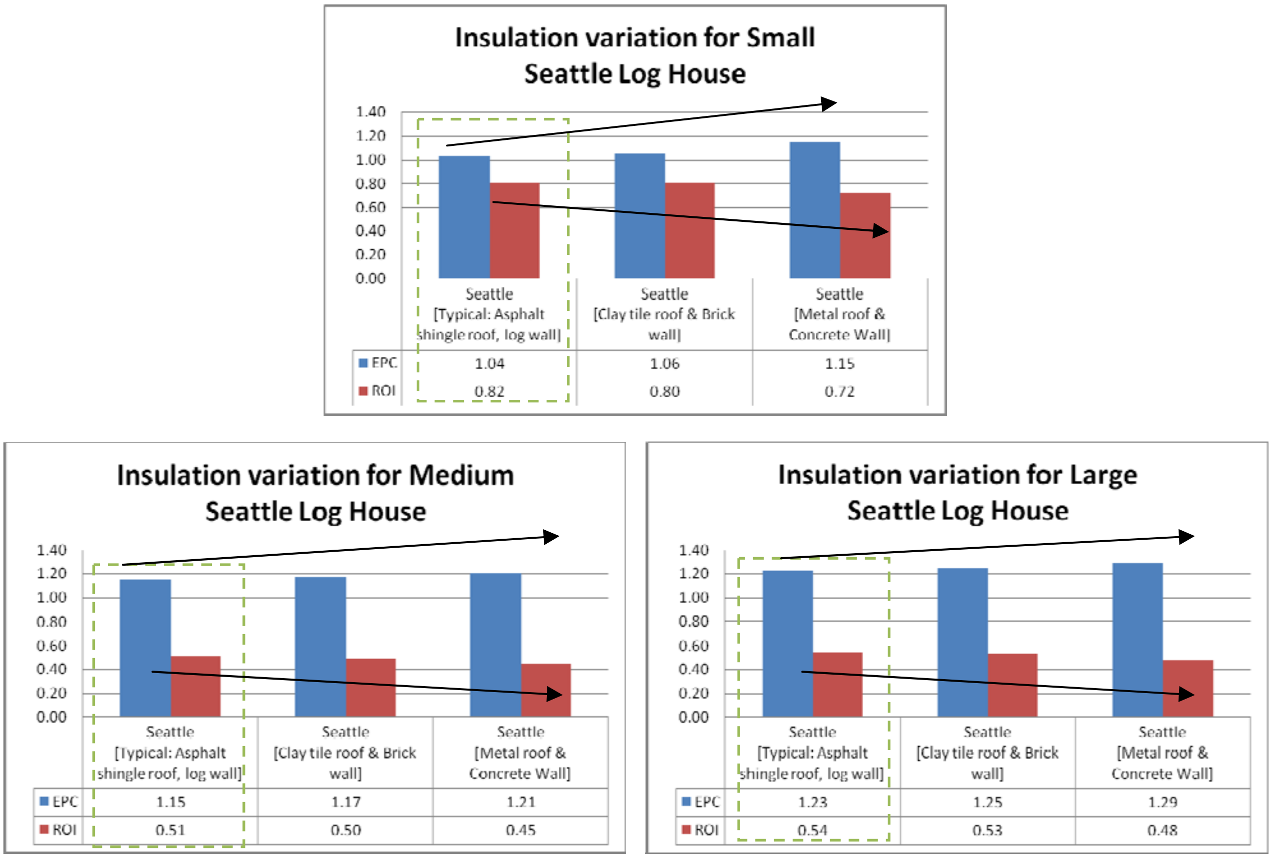


Figure 28. Insulation Variation for different size of houses in Seattle

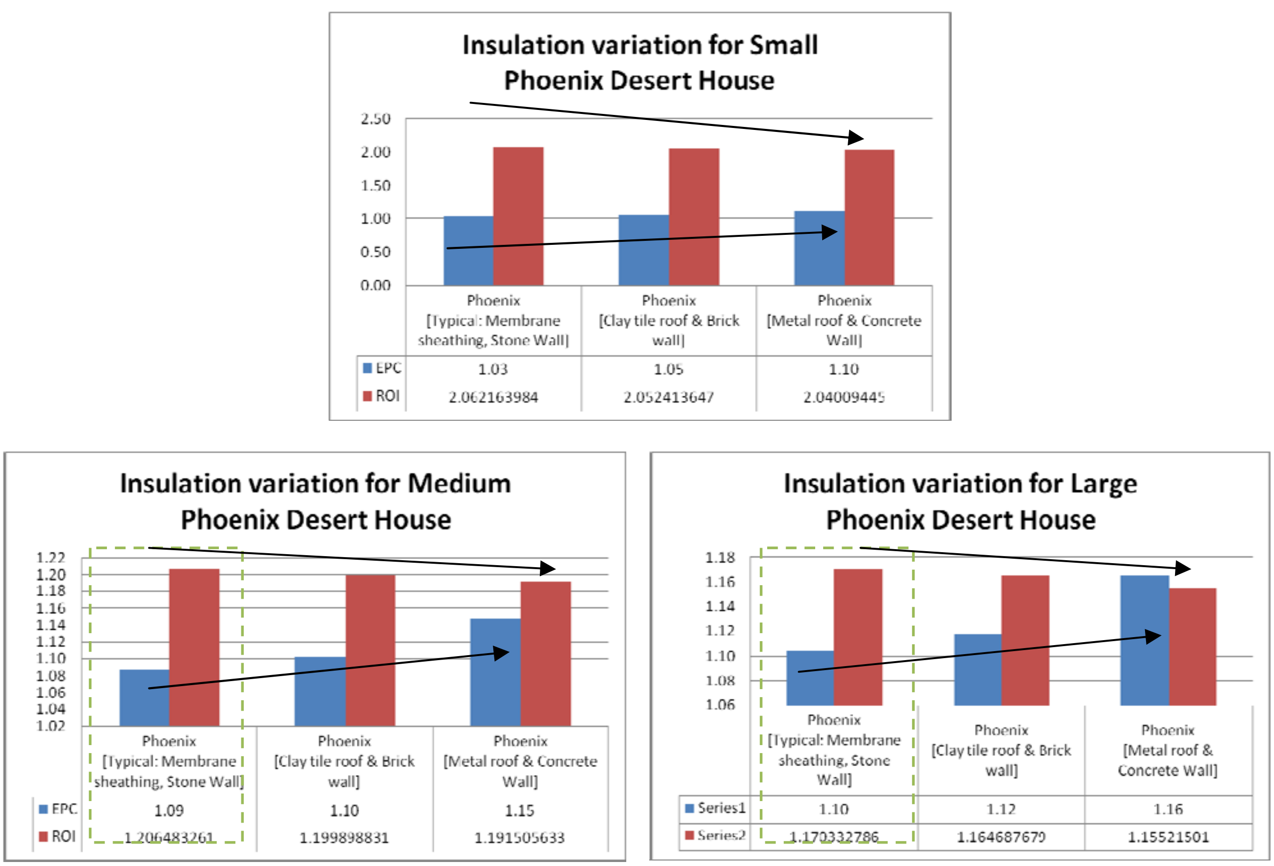


Figure 29. Insulation variation for different types of houses in Phoenix

windows (U: 1.7 W/m²K, SHGC: 0.5).

- Variation 1: Clay tile Roof (U:0.179 W/m²K, ε: 0.39), Brick Wall (U:0.283 W/m²K, ε: 0.92), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5)
- Variation 2: Metal Roof (U:0.227 W/m²K, ε: 0.462), Concrete Wall (U:0.434 W/m²K, ε: 0.92), Double Glazed windows (U: 1.7 W/m²K, SHGC: 0.5)

As a result the study shows that the higher the EPC value the lower the ROI, since the energy savings from better insulated buildings to conserve the interior temperature reflects into the payback time of the photovoltaic as well by being able to sell more energy back to the grid than use it for domestic use.

The reference used for this savings was the typical construction for the area which in this case was the log and desert construction, which obviously seem to be the most effective insulation for each particular region. Additionally, also note that as the house gets bigger, the ROI gets lower as previously mentioned, since the bigger the house the more energy required to sustain it. Also note that, the due to higher levels of solar radiation, homes in phoenix, have a better return of investment since it allows for higher productions of energy in addition to wider roof area to install more modules.

4.7. Roof Variation (different active areas, one layout)

When we study the architectural articulation effect on the economics of photovoltaics, we used a small residence layout but we varied the roof and the angle available for photovoltaics, it gives us an interesting result:

While the Energy Performance Coefficient in energy demand remains stable since the insulation of the examples is the same (Asphalt Shingles Roof (U:0.235, ε: 0.462), Log Wall (U:0.264, ε: 0.91), Double Glazed windows (U: 1.7, SHGC: 0.5), the Return of Investment varies drastically because usually for the same layout of house the dutch and flat roof provides much more area available for solar panels.

4.8. Roof Variation (same active areas, different layout)

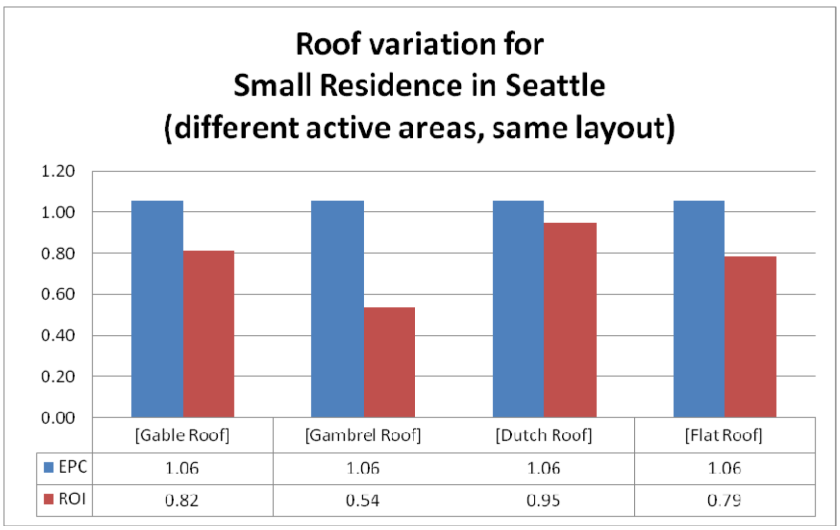


Figure 30. Roof variation effect (Different active area, same architectural Layout)

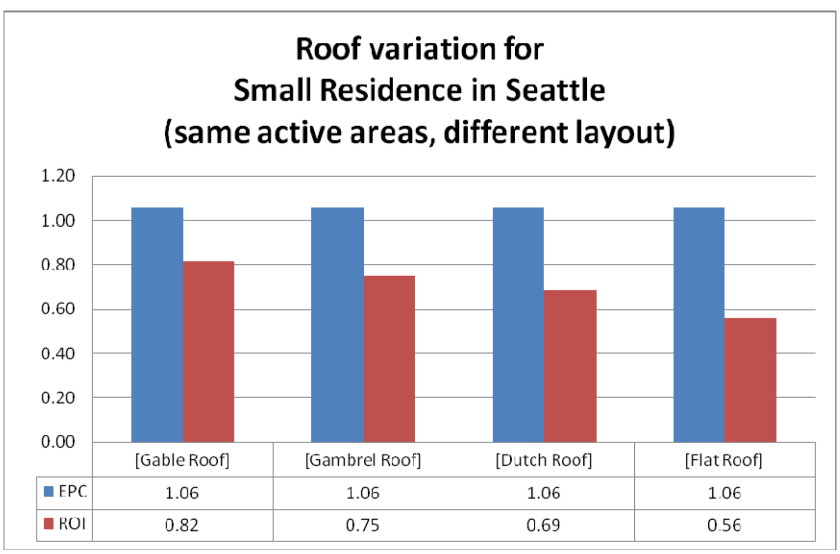


Figure 31. Roof variation effect (Same active areas, different roof angle)

However, if we study the effect on the return of investment having the exact same available active area for solar panels ($80m^2$) and the rest of the paramenter are fixed, we noticed that event though the EPC is stable, the return of investment is represented in a hierarchy since in the case of flat roofs, the angle reduce the efficiency of the solar panels to the least possible return.

On the other hand, the combination of angles between dutch roof (South 0º and South 45º) and gambrel roof (South 60º and South 45º) put them in a better possition of terms of return , but the best possible condition is the gable roof since all the available active area is at an even angle that allows the maximum harvesting of solar radiation (South 45º), even though the ideal angle for each particular region would be something similar to their own latitude and hemisphere.

4.9. Orientation Variation

The orientation of the active area certainly creates an effect on the energy harvesting. In this example we chose 5 different possible typical orientations in the northern hemisphere: West, South-West, South, South-East and East, while keeping the same geometry and angle of the roof. Just the orientation of the roof reduces the Return of Investment 21% at 45ºoffset rotation and 79% reduction at a 90º offset rotation.

Therefore is not a proportional reduction but an exponential one. The following graph shows that the ROI follows the pattern of the energy generation.

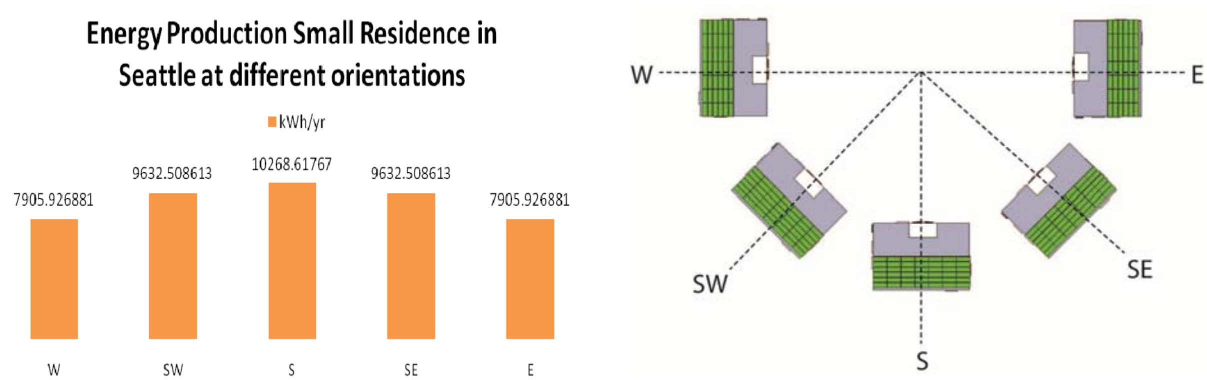


Figure 32. Energy Production at different orientations

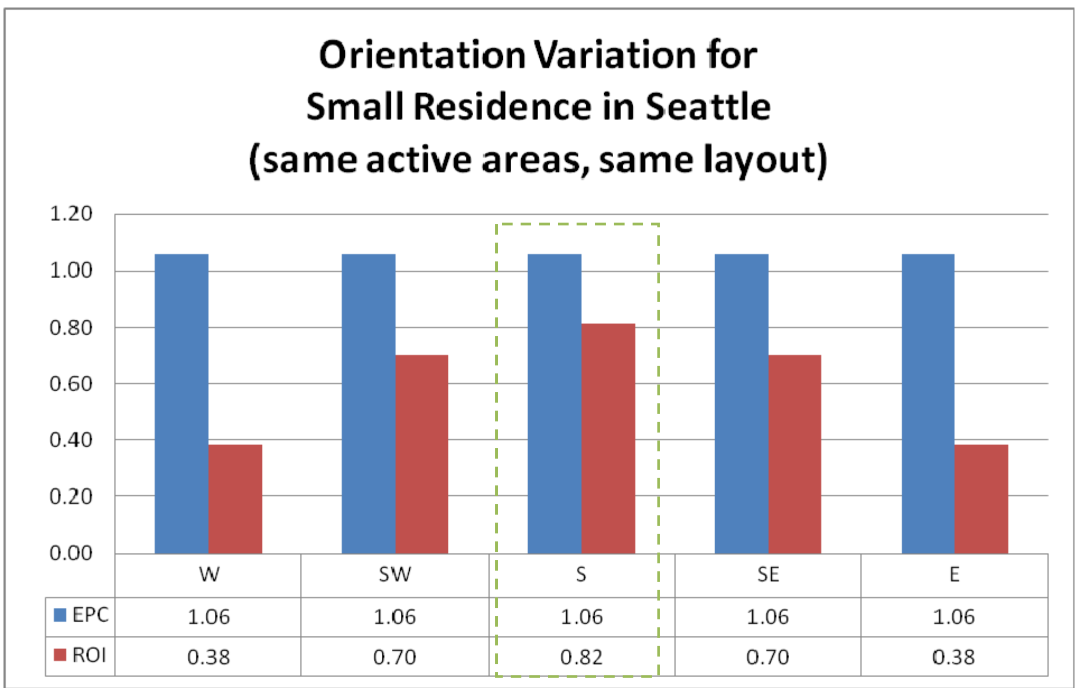


Figure 33. Orientation Variation (Same active areas, same layout)

4.10. Location Variation

The other main change that a house can take into consideration is the location. The location of the residence make a big impact, because just in the United States there are 8 different radiation levels according to PVWatts Viewer. The four locations that we have taken into consideration, (1) Phoenix, AZ [6.18 kWh/m²/yr] (2) Miami, FL [5.33

kWh/m²/yr] (3) New York City, NY [4.63 kWh/m²/yr] and (4) Seattle, WA [3.6 kWh/m²/yr], are metropolitan cities located at the 4 different corners of the country with 4 very drastic radiation levels. Let's say a that we have a small house, with gable roof being the most effective of the four typologies as previously mentioned and one fixed architectural design. We reproduce this residence with the same insulation, construction techniques and mechanical system at these cities and the result shows that even though the return of investment increase as the radiation that the house is exposed to increases, the energy performance (EPC) varies as the house is required to compensate for the temperature and humidity of the various regions, showing in this case that the best possible scenario would be a gable roof house in Miami with the best possible insulation that would require less energy and less payback period.

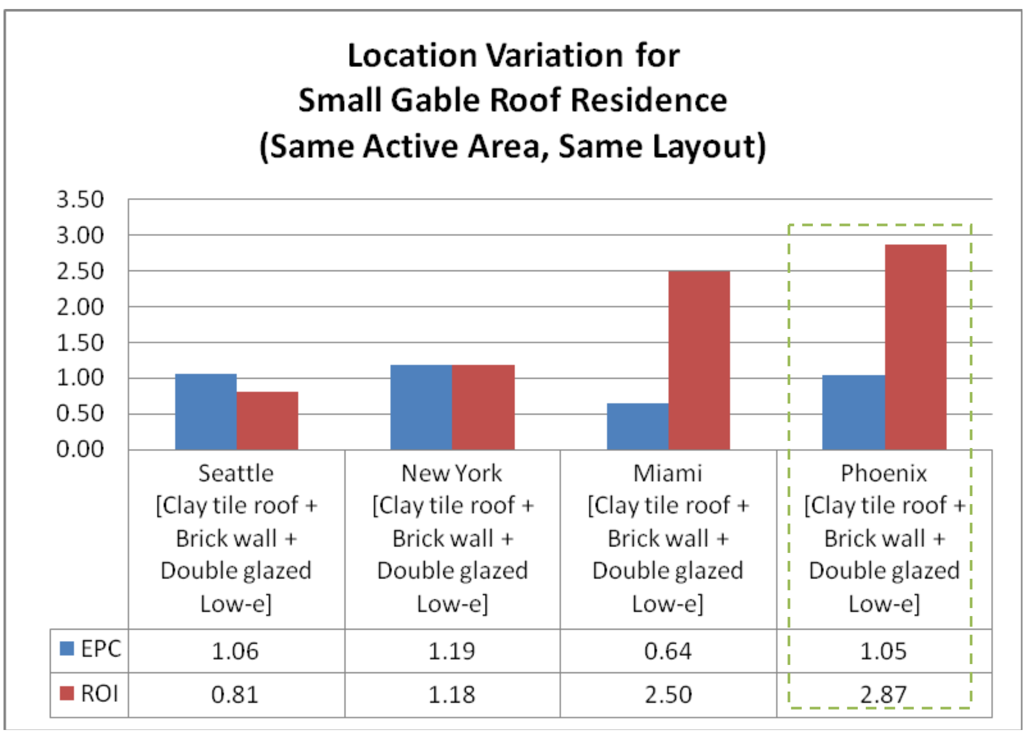


Figure 34. Location variation (same active, same layout)

4.11. Orientation and Roof Variation

Given the same location, mechanical system, architectural layout, insulation properties and active area but we vary the orientation and configuration of the roof at the same time, we find that each set of possibilities offer a stable Energy Performance that may change accordingly to the location but a widely variable range of return of investment indexes that will be somewhat similar in every region. Based on this location (Seattle) de design that offers more return is the gable roof towards the true south. The least advantageous angles in every design seem to be the gambrel roof at East and West exposure and the Gable roof at East and West exposure as well. The orientation of the desert home (flat) seems to be irrelevant, since the whole surface is always exposed at all angles.

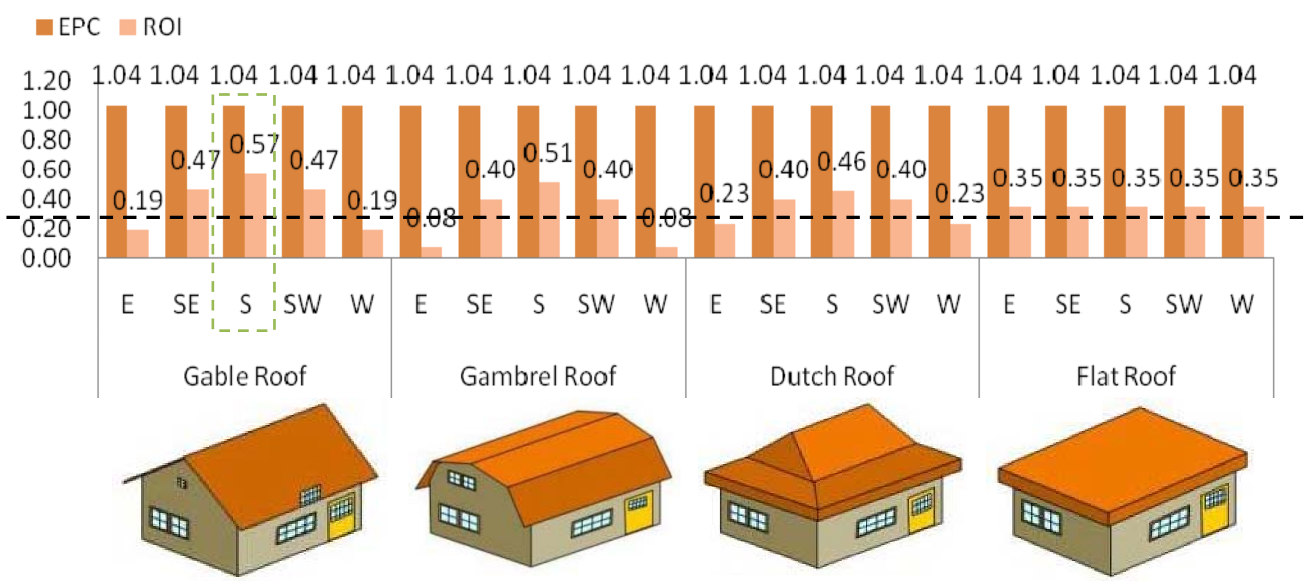


Figure 35. EPC and ROI Comparison with rotation and roof variation

- - - - Median ROI

Interesting enough after the flat roof, Dutch Roof brings the least variable effect on ROI with only 50% decrease at a 90º rotation, later gable roof with 67% decrease at 90º rotation and finally gambrel roof at 84% decrease at 90º rotation. When we put photovoltaics in vertical surfaces and also explore these orientations the results varies as well. It seems that the efficiency is drastically dropped since it is the worst possible position for a photovoltaic to be placed and therefore the return of investment is very low as well. However, depending on the area and other settings these can be improved.

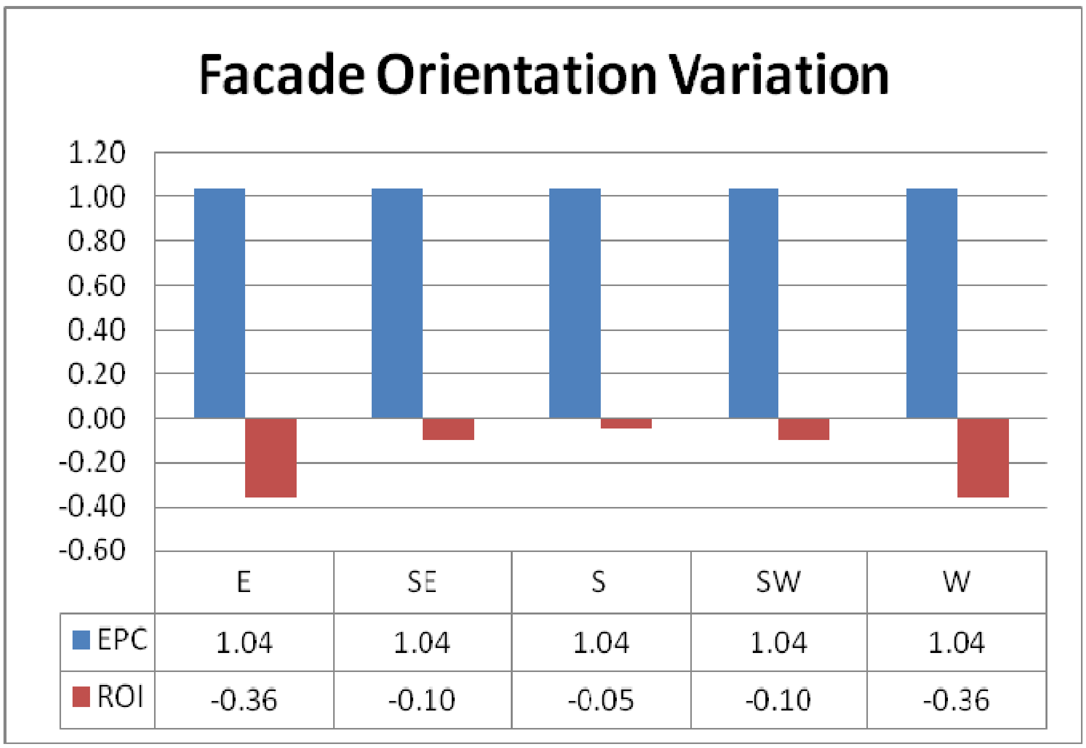


Figure 36. Facade Orientation Variation Effects

4.12. Photovoltaics in Building Accessories

The following are examples of the use of photovoltaics into building accessories throughout the world. The articulation of the architecture and recent technologies of photovoltaics allows for the maximization of their functions , as well as it permits the optimization of space while making photovoltaics a new trendy style in architecture. According to Wassim Bahr in his presentation for the Green Retrofit Conference, "Integration of Shading Devices and Photovoltaics Panels into Existing Building Facades" photovoltaics can be integrated into roofs as previously explored, façade through building integrated photovoltaics (BIPV), on shading devices and on wall cladding (Bahr 2009).

<u>Shading devices</u>

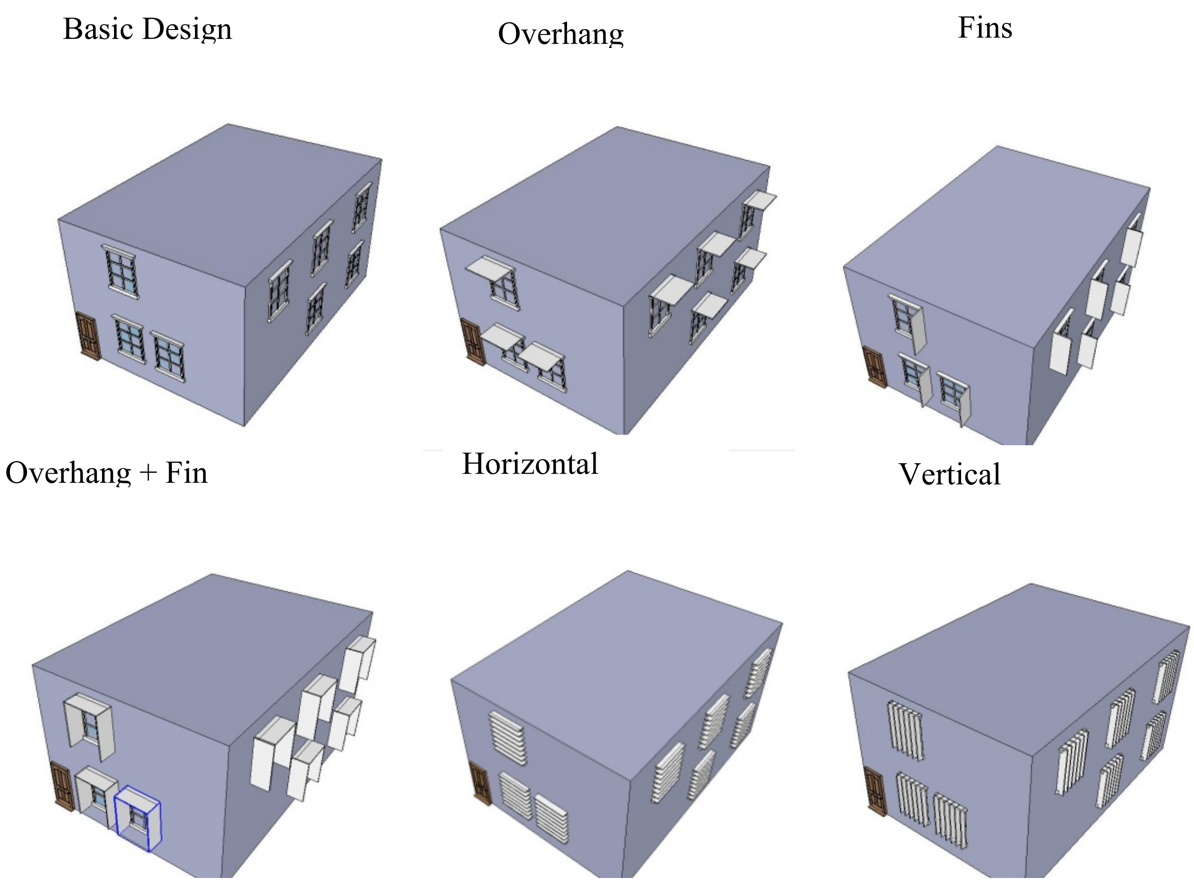


Figure 37. Types of shading devices available to incorporate PVs.

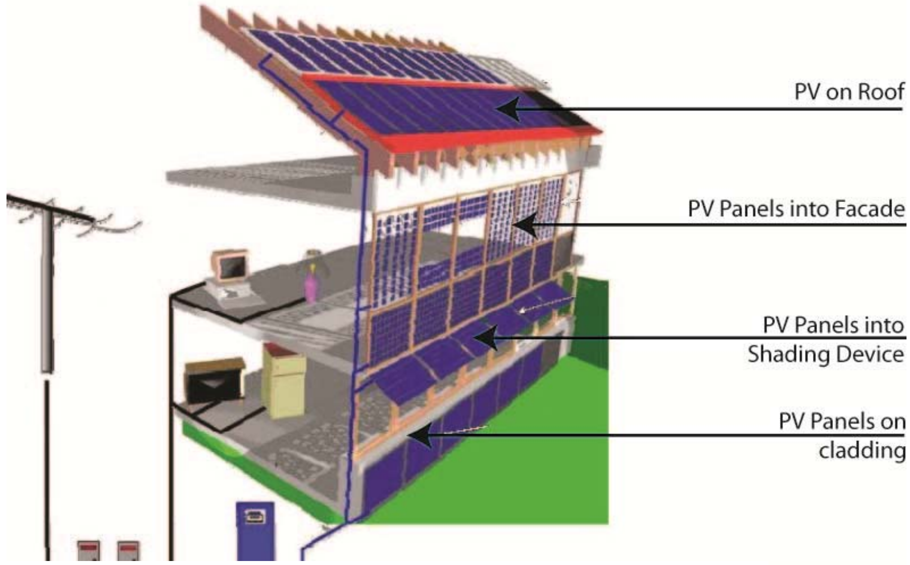


Figure 41. Photovoltaics in Building Accesories

Figure 40. Photovoltaics in shading devices

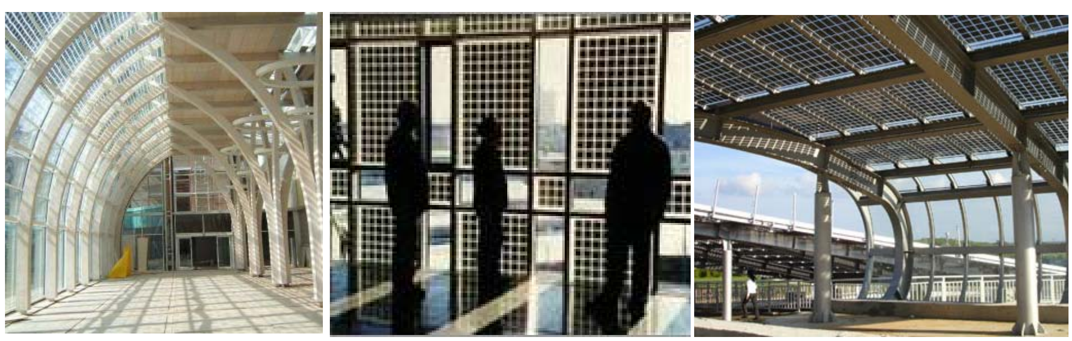


Figure 40. BIPV in Facades

Figure 40. Photovoltaics in cladding

According to Bahr, the integration of photovoltaics in shading devices, not only allows for bigger area of energy production but also improves thermal comfort, by reducing air conditioned thermal loads, and reduction of artificial lighting. Additionally, it allows visual comfort, more privacy and more glass area.

Therefore, through this study, different types of shading devices were tried and incorporated them to a basic design. The photovoltaics were exposed to the surface of the shading devices that allow the maximum harvesting of energy. Therefore, with one single configuration of construction and fenestrations, the active area (PV area) varies from type of shading device to the other, but the principle of ROI and EPC compensate accordingly. Figure 43 and 44 shows the comparison between the different scenarios if only the shading devices vary but not the interior architectural design of the house. According to this comparison fins are not very encouraging to use for PVs since they don't protect from sunlight at midday, their active surface area is only exposed to the sun, half of the day and as previously mentioned the vertical position (90º) at any orientation is the least beneficial design decision for PVs, while overhangs and horizontal louvers are always exposed throughout the whole day and therefore more economically feasible, even though for the purpose of this study only surfaces at 0º were used. If these angles, at least for the horizontal louvers were to increase the return of investment would be even higher.

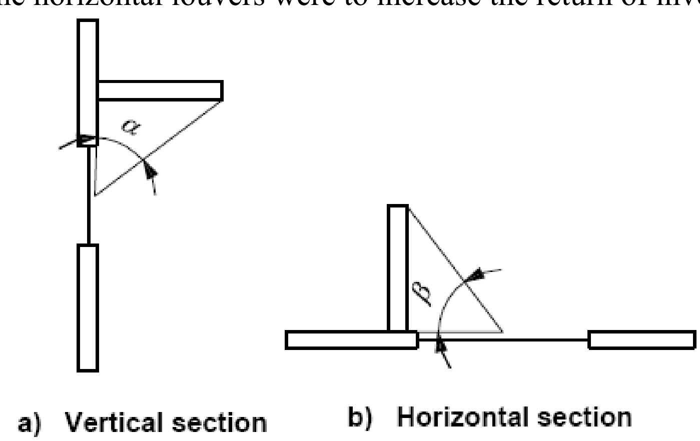


Figure 42. Shading devices angle parameter

For this example (Figure 44), Phoenix was chosen due to its harsh climate conditions and since it is the location that would take more advantage of the shading devices therefore, the energy performance of the house has changed as well, because these devices have allowed lower cooling loads and more thermal comfort.

In the second case Seattle (Figure 43), the performance (EPC) reacts in an opposite way, because shading devices limit solar radiation into the house which is very restricted in this city due to its cold climatic conditions throughout the year. In this case the shading devices do not help in terms of performance forcing the design to require more energy for heating but the profile of the return of investment (ROI) is quite similar suggesting that even though fins do allow solar radiation at midday to compensate for a better energy performance demand of the house (EPC), the investment for PVs with these devices is not appropriate even under these conditions. Also note that for this comparison the active areas are only part of the shading devices, since we are not adding the active areas used in previous analysis (Roof area).

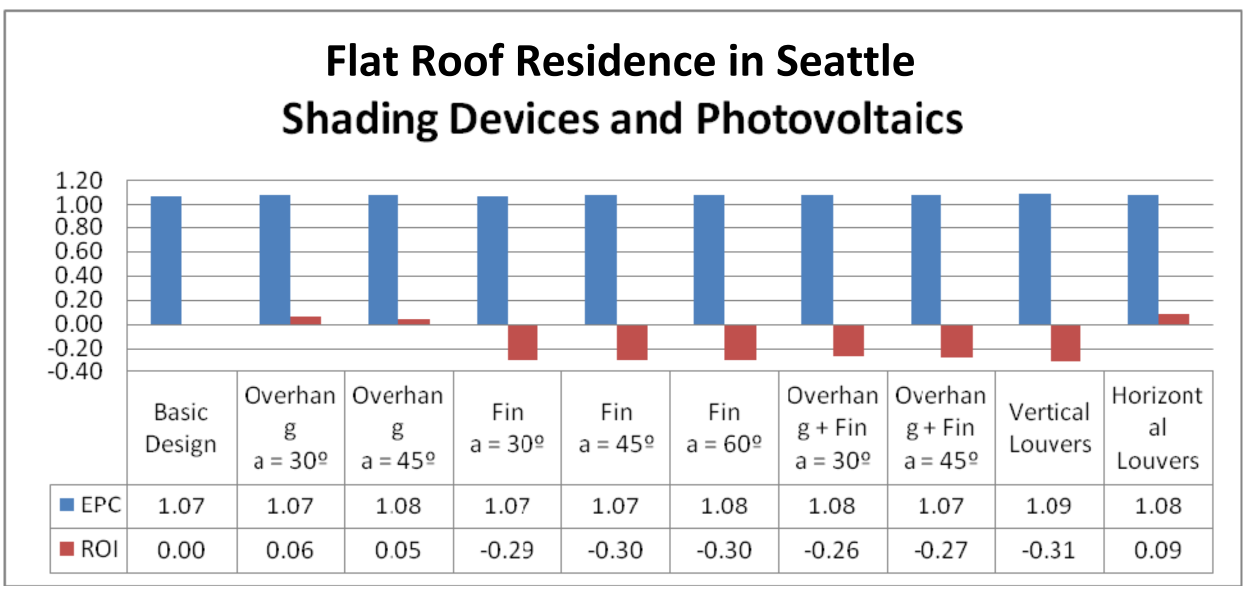


Figure 43. Comparison of EPC and ROI in Shading device with photovoltaics in Phoenix

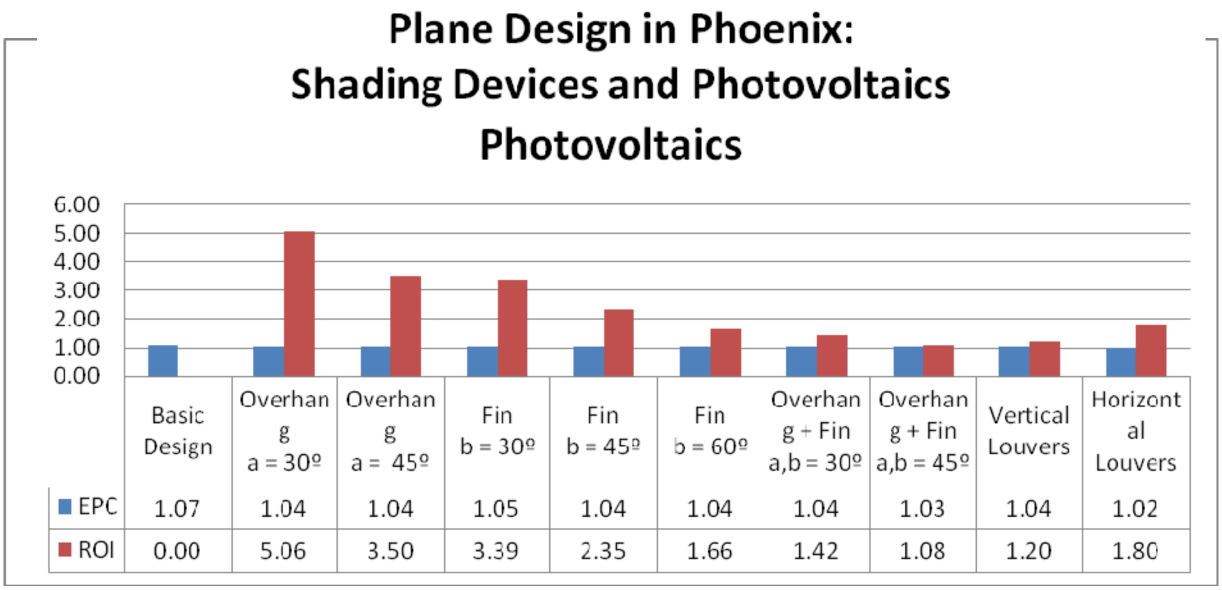


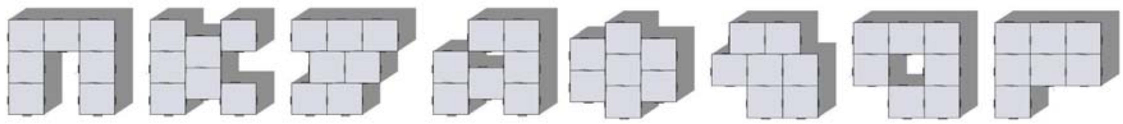
Figure 44 Comparison of EPC and ROI in Shading device with photovoltaics in Phoenix

Thus, the payback period and return of investment is much higher since the initial capital cost of photovoltaics is lower (less active area) and the energy savings created by them is higher than in the previous evaluations of roof alterations.

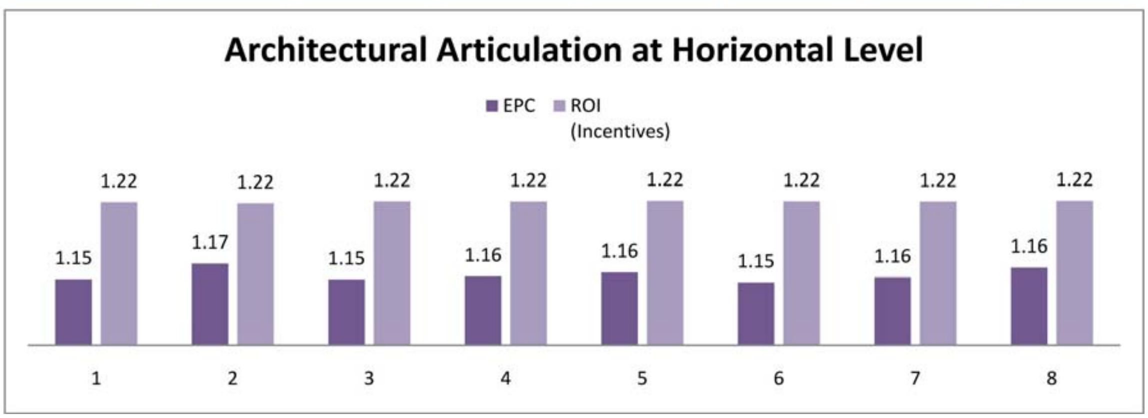
4.13. Articulation

Architectural articulation shows more drastic results when is articulated in a vertical way than when is articulated in a horizontal way. However, the results for return of investment do not vary a lot since the change on the performance is not drastic and the number of photovoltaic modules is the same.

Therefore, even though the articulation is very is dramatic and provides shading to different fenestrations it causes few improvements on the energy performance. Insulation and shading devices may work as better improvers of this purpose. As we can see on Figure 44, there are eight variations of a residence, with the same amount of roof area, and inside volume, the same number of windows and doors and the same orientation. The variation in the perimeter of the residence created a small range of 1.15 and 1.16 in energy performance, while the variation in the facade by created overhangs provides a wider range between 1.16 and 1.13 but neither of these 2 differences, big enough to trigger the return of investment ratio. Therefore, showing that architectural articulation does not really create a big effect on performance but perhaps selection of materials creates a higher effect on the return.



	1	2	3	4	5	6	7	8
EPC	**1.15**	**1.17**	**1.15**	**1.16**	**1.16**	**1.15**	**1.16**	**1.16**
ROI (Incentives)	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**



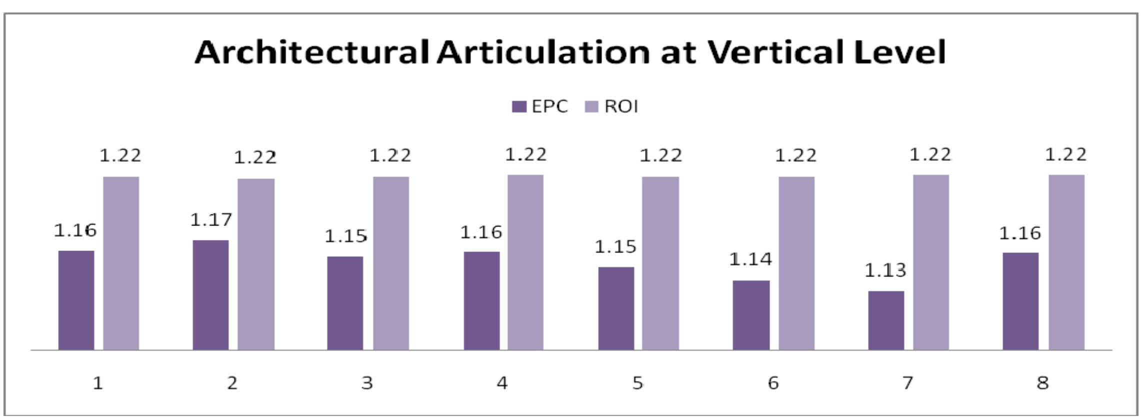


Figure 45. Architectural Articulation in plan view and elevation

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The analysis taking place while comparing economics and geometry emphasized the fact that architecture and technology can work together. This study shows that each different architectural design is unique and its articulation can potentially bring savings in

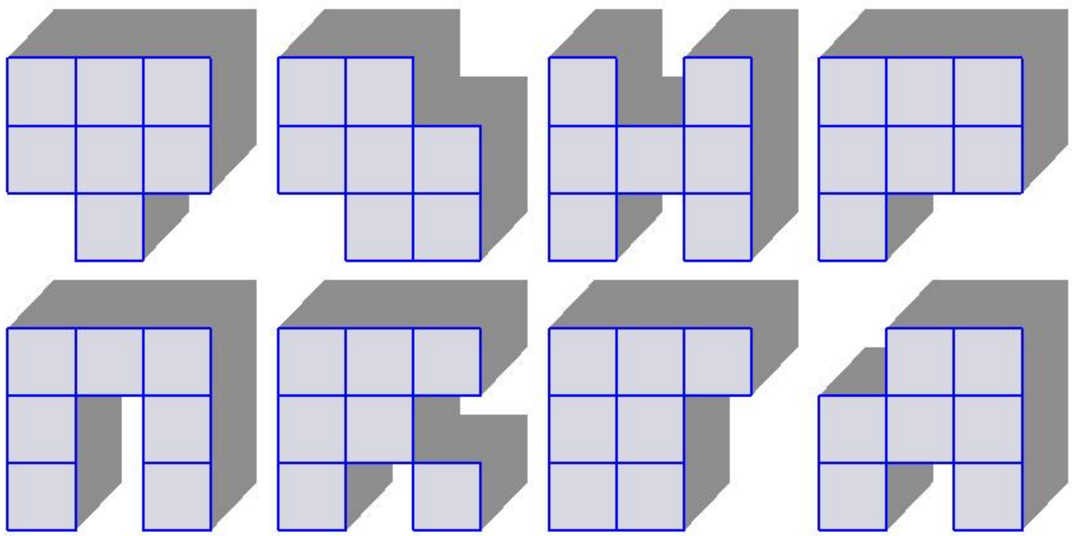


Figure 46. Shadow projections and architectural articulation with the same volumes and roof areas.

terms of performance when is well thought. In overall terms, in a cities exposed to high levels of solar radiation like Miami and Phoenix, and where a design is properly massage to fit the requirements (climatic and aesthetic), the high articulation of the design would bring the energy demand down, because the articulation brings shading and protection from solar radiation to the different fenestrations throughout the house, as mentioned previously. Therefore, it constitutes a lower energy demand while keeping the same roof area available for photovoltaics. On the other hand residences in cities with lower levels of radiation like New York and Seattle, the articulation of the house should be rather simple to allow for bigger amounts of solar radiation coming into the inhabitable spaces and thus lowering the energy demand as well, while keeping the same available area for photovoltaics on the roof.

Shading devices and articulation combined could be much more effective than the different roof configurations effects on the solar panels efficiencies but both features can be included in a design for the best possible results. As mentioned, the shading devices offer a very interesting solution for both saving and production of energy, in and outside the house, but certainly insulation also plays an important part on the configuration of the design.

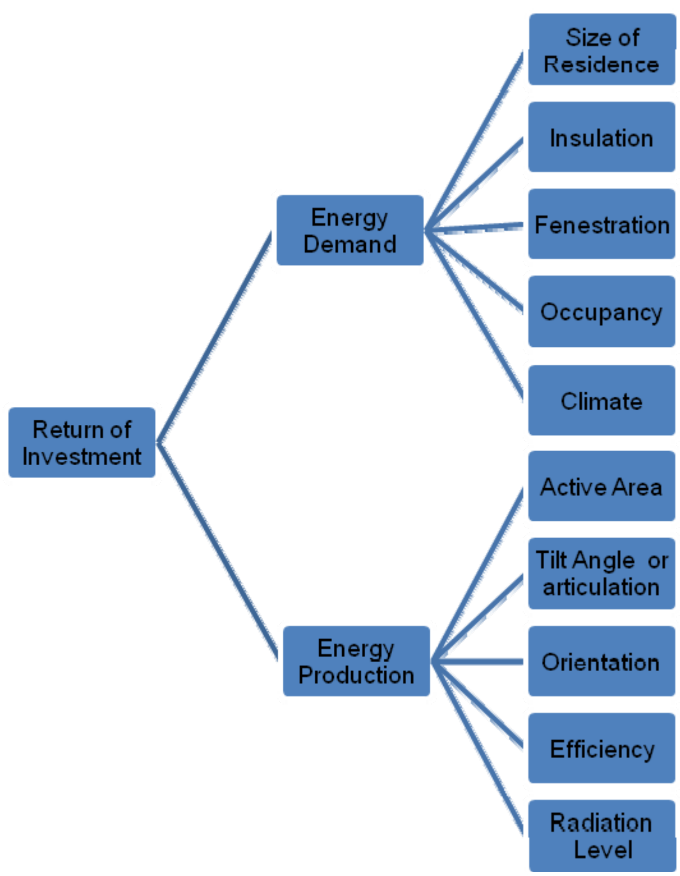
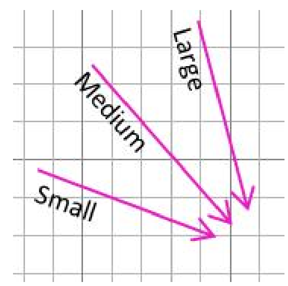


Figure 47. Drivers of ROI of PV on Architectural Elements

:h design, but they can certainly make a c

After gathering all this information, it was concluded that the main drivers of the return of investment of photovoltaics in a residence are the energy demand and the energy production, which are later broken down into ten factors like size of residence, insulation, fenestration, occupancy, climate, active area, tilt angle and articulation, orientation, efficiency and radiation level . Fig 49, explains better this relationship.

On the other hand, if we put in a graphical way all the previous information from figures 26 through 46, having a base case of Seattle Small Residence with Clay tile roof, brick wall and double glazed tow-e, we discovered the following trends:



(1) The more insulation improvement, the more return of investment. It also seems that this trend is shown on a slope that changes depending on the size of the house.

(2) The more active area available in a typology (stable EPC), the more return of investment, since the maximization of area allows for a higher production of energy.

(3) Proportional sizing of a house creates an drastic increase in the energy demand, andthe return of investment is slowly reduced as well. Therefore, the smaller the house the more predictable return of investment, and usually the higher return of investment.

(4) It seems that there is a hierarchy in the importance of architectural element use for photovoltaics. Some of these elements' order vary depending on the radiation level and climate like: Overhangs, louvers, fins, and architectural

articulation in general, while others are stable for any particular climate and radiation like: walls and roofs.

Each architectural design is different and the 10 drivers may vary in a different way. Therefore, each design has to be evaluated separately, and even though some architectural elements' ROI may overlap with each other Fig. 50 gives a general idea of how this spectrum works, as an general tendency in most designs. This figure was based on the recollection of previous information. Note that the lower part of the graph refers to the comparison between the results of figures 43 and 44 that shows the difference on the effects of PVs on shading devices at different cities.

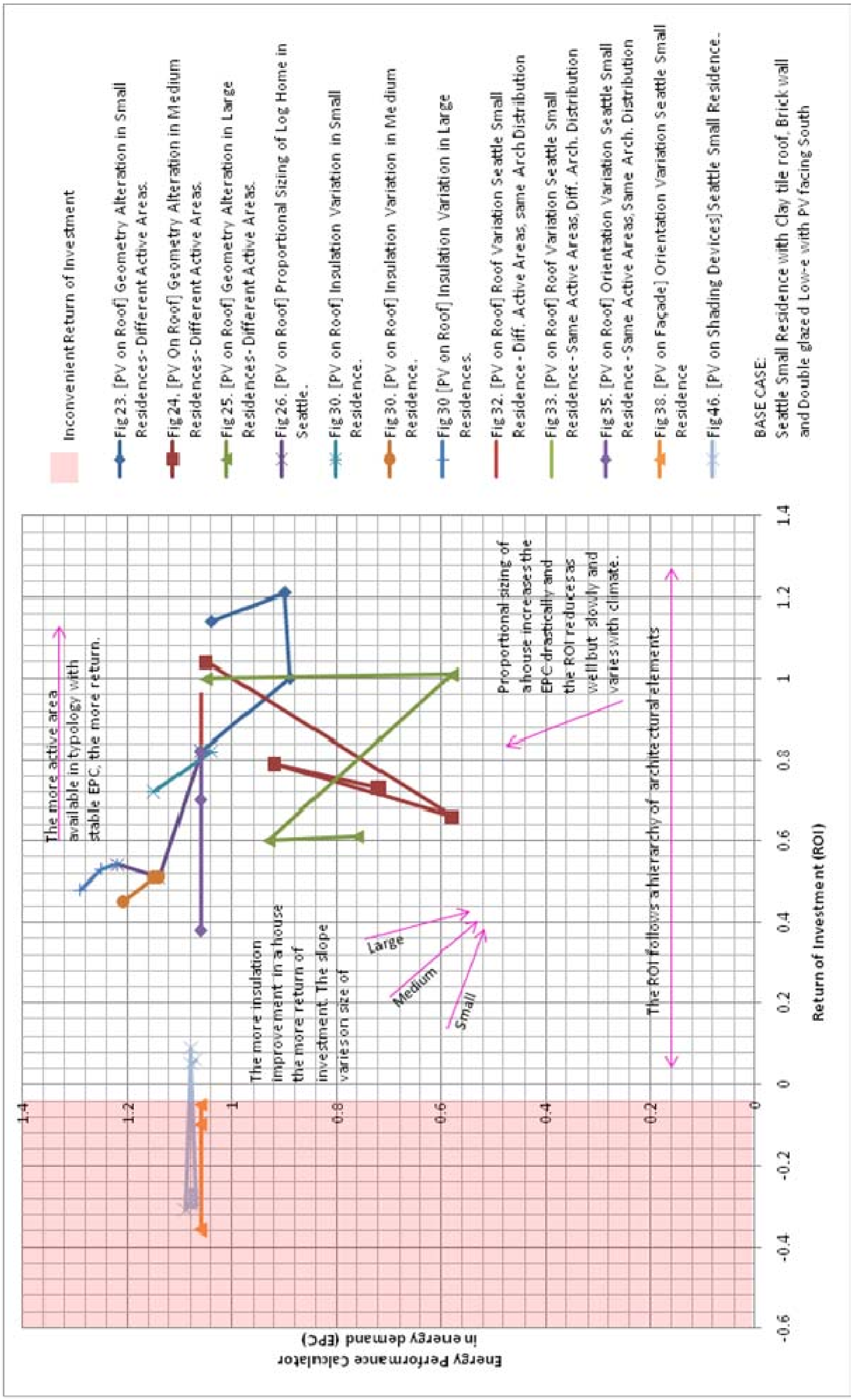


Figure 48. EPC and ROI relationship for previous figures.

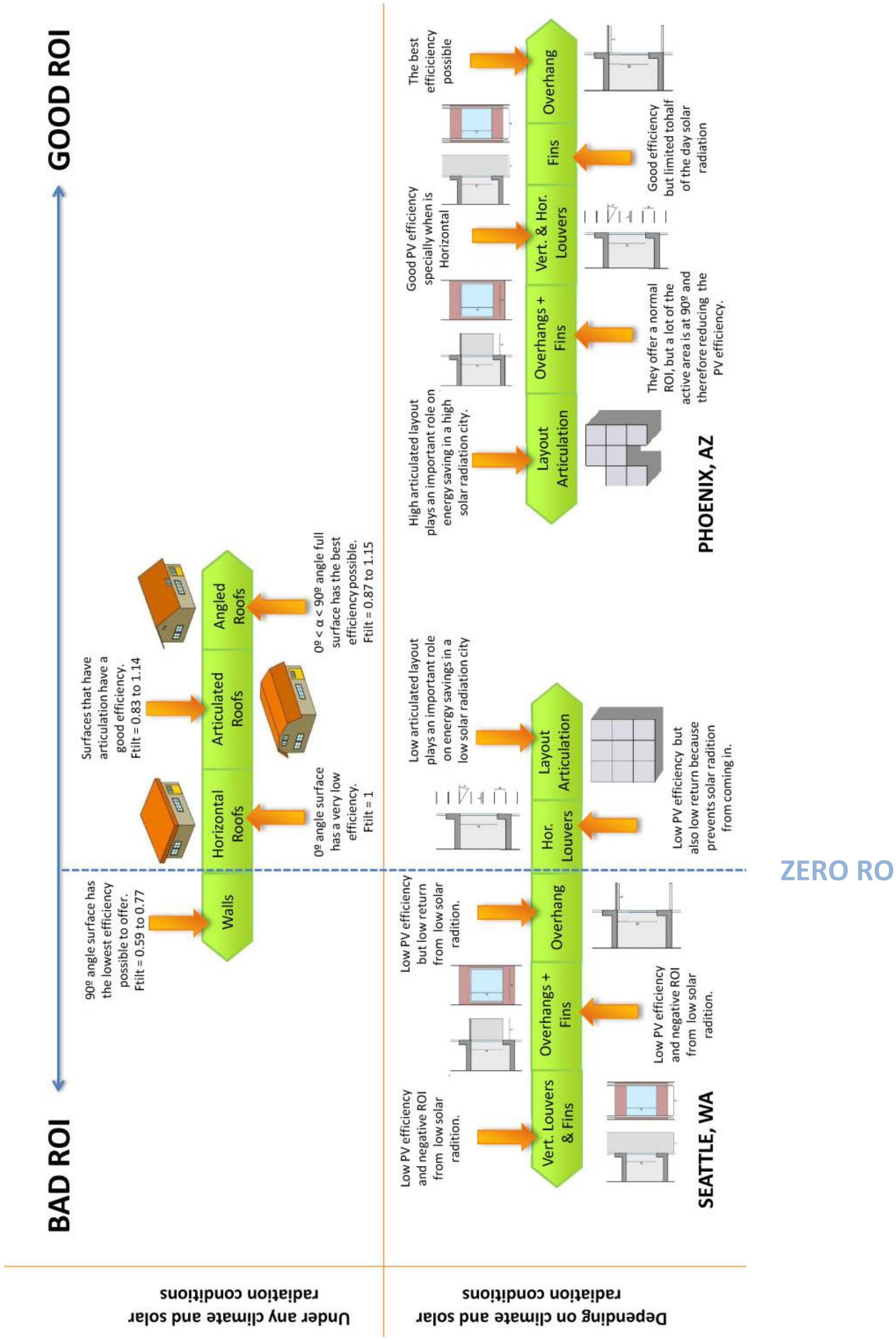
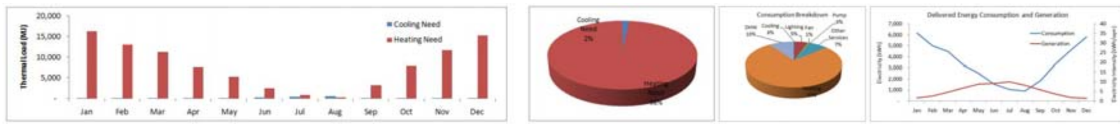


Figure 49. Hierarchy of PV use on Architectural Components

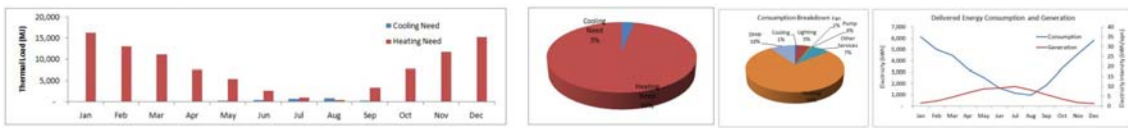
APPENDIX A

ENERGY DEMAND AND PRODUCTION OF EACH DESIGN

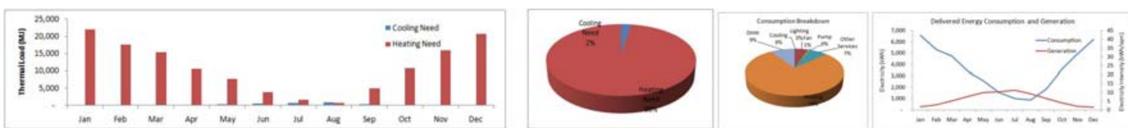
Seattle / Gable Roof / Small Residence / Typical Insulation



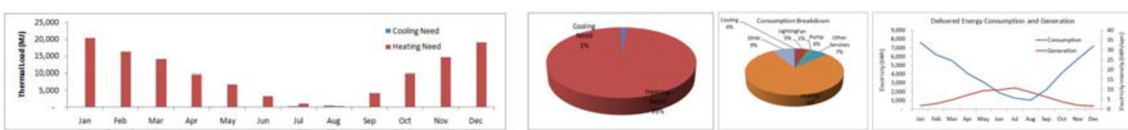
Seattle / Gable Roof / Small Residence / Insulation 2



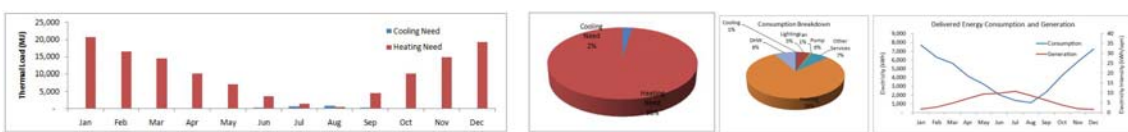
Seattle / Gable Roof / Small Residence / Insulation 3



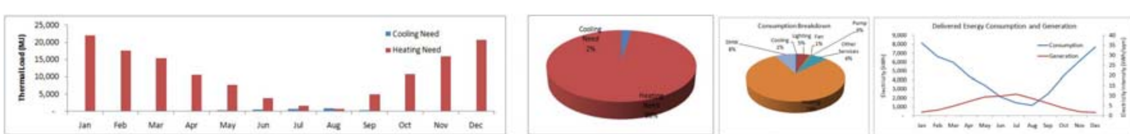
Seattle / Gable Roof / Medium Residence / Typical Insulation



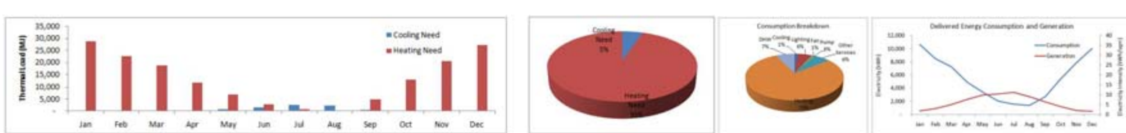
Seattle / Gable Roof / Medium Residence / Insulation 2



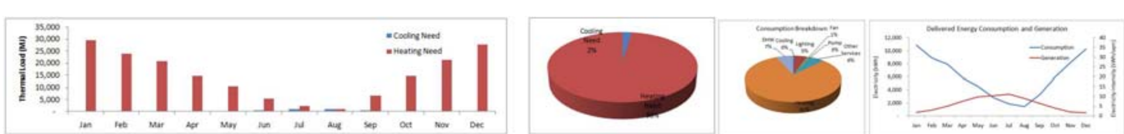
Seattle / Gable Roof / Medium Residence / Insulation 3



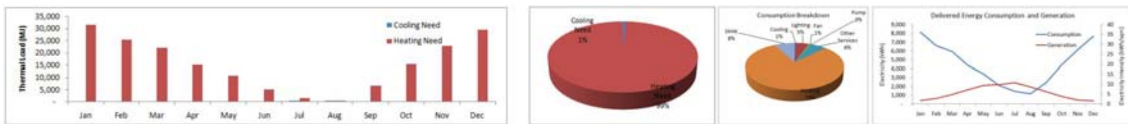
Seattle / Gable Roof / Large Residence / Insulation Typical



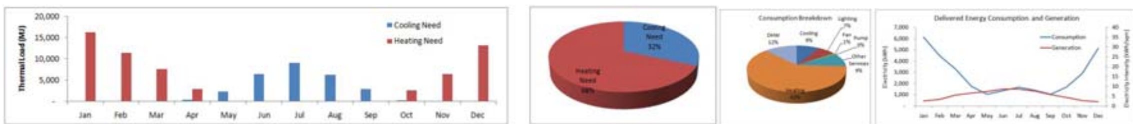
Seattle / Gable Roof / Large Residence / Insulation 2



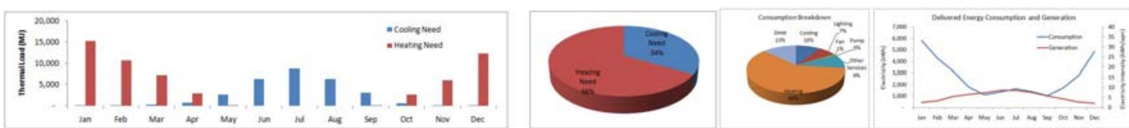
Seattle / Gable Roof / Large Residence / Insulation 3



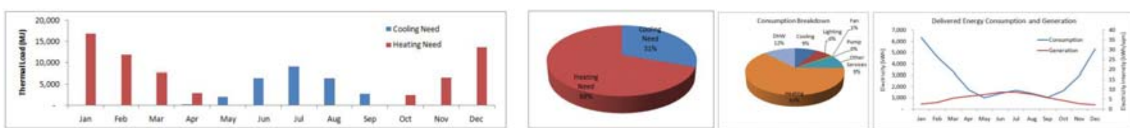
New York/ Gambrel Roof / Small Residence / Insulation Typical



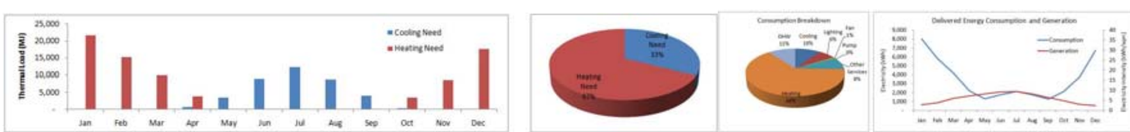
New York/ Gambrel Roof / Small Residence / Insulation 2



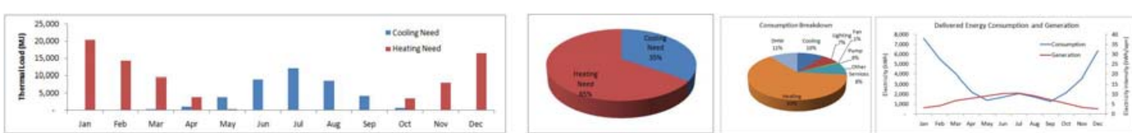
New York/ Gambrel Roof / Small Residence / Insulation 3



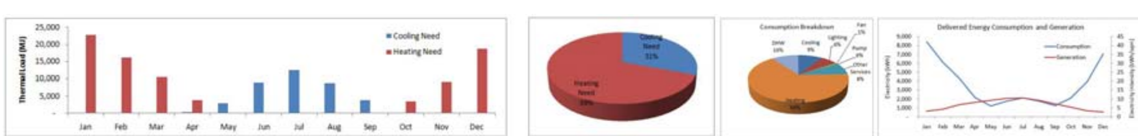
New York/ Gambrel Roof / Medium Residence / Insulation Typical



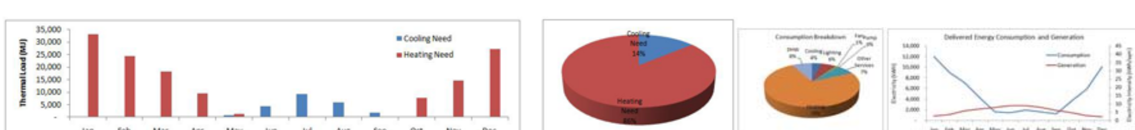
New York/ Gambrel Roof / Medium Residence / Insulation 2



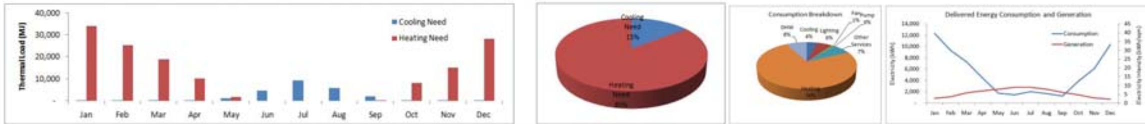
New York/ Gambrel Roof / Medium Residence / Insulation 3



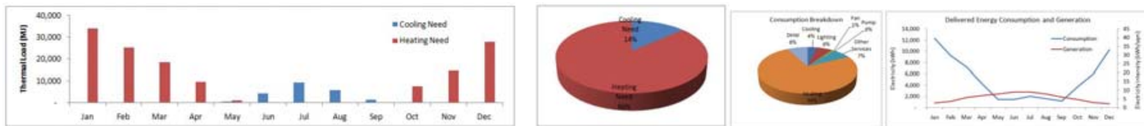
New York/ Gambrel Roof / Large Residence / Insulation Typical



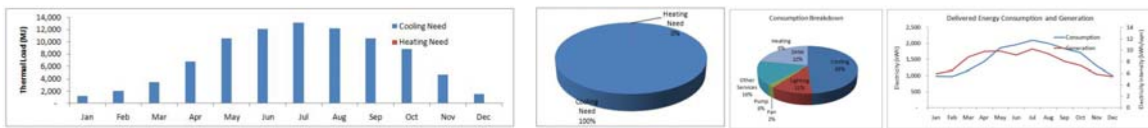
New York/ Gambrel Roof / Large Residence / Insulation 2



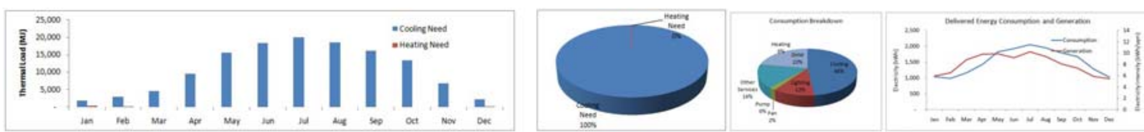
New York/ Gambrel Roof / Large Residence / Insulation 3



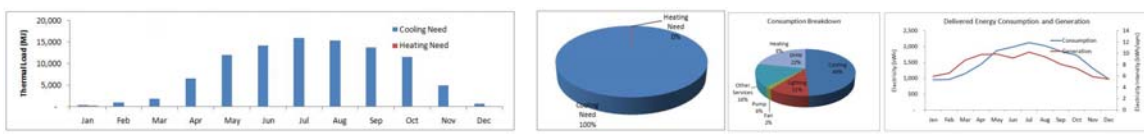
Miami/ Dutch Roof / Small Residence / Insulation Typical



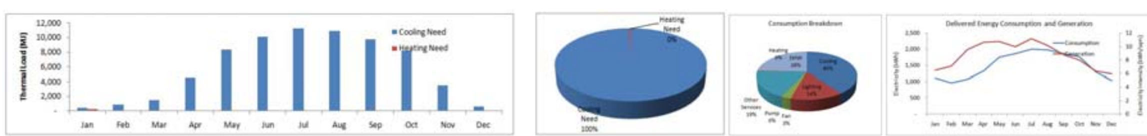
Miami/ Dutch Roof / Small Residence / Insulation 2



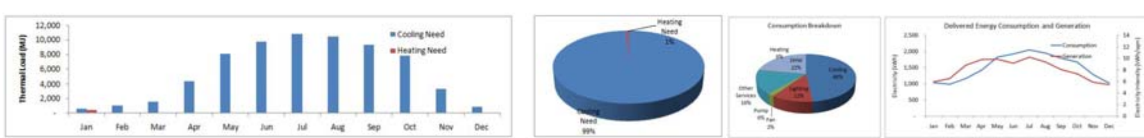
Miami/ Dutch Roof / Small Residence / Insulation 3



Miami/ Dutch Roof / Medium Residence / Insulation Typical



Miami/ Dutch Roof / Medium Residence / Insulation 2



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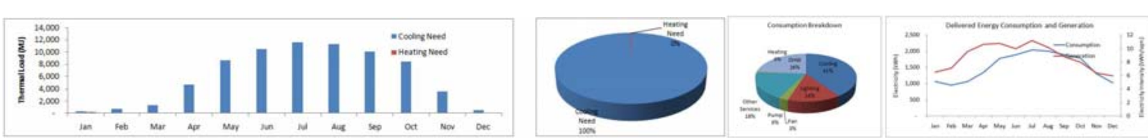
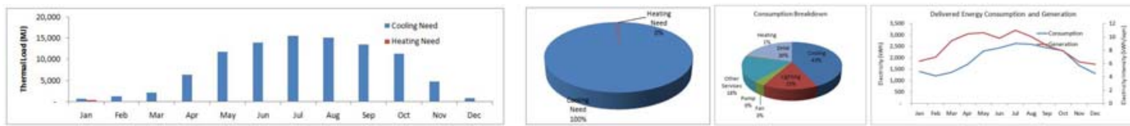
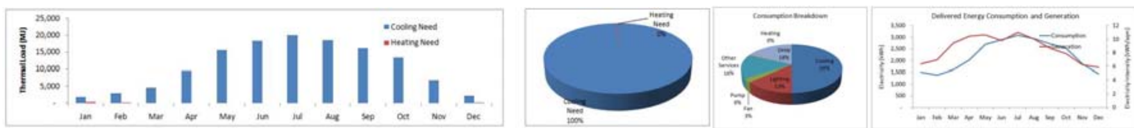


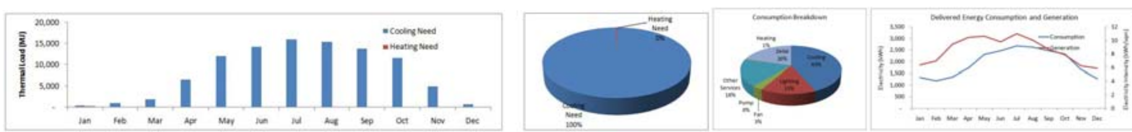
Miami/ Dutch Roof / Large Residence / Insulation Typical



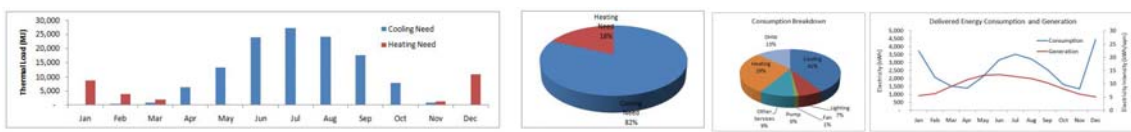
Miami/ Dutch Roof / Large Residence / Insulation 2



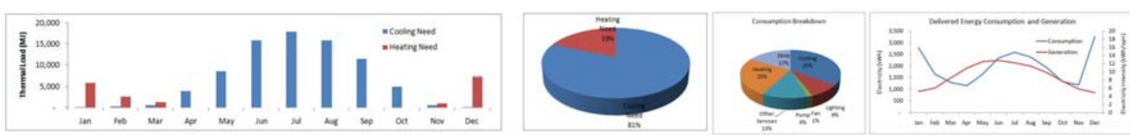
Miami/ Dutch Roof / Large Residence / Insulation 3



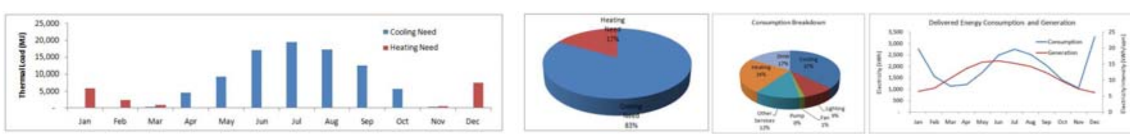
Phoenix / Flat Roof / Small Residence / Insulation Typical



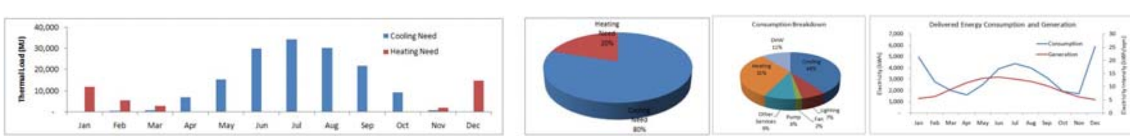
Phoenix / Flat Roof / Small Residence / Insulation 2



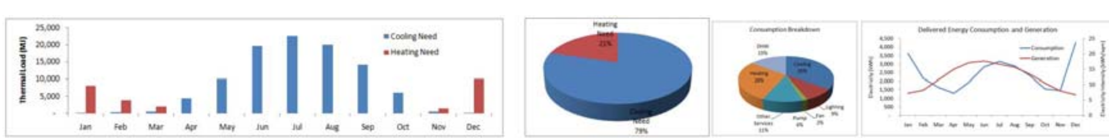
Phoenix / Flat Roof / Small Residence / Insulation 3



Phoenix / Flat Roof / Medium Residence / Insulation Typical



Phoenix / Flat Roof / Medium Residence / Insulation 2



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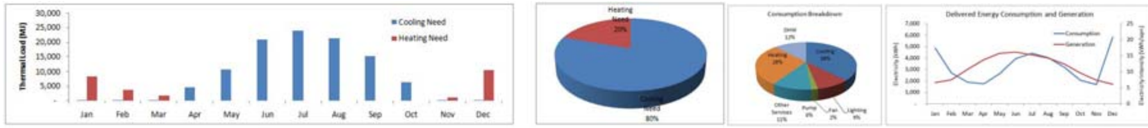
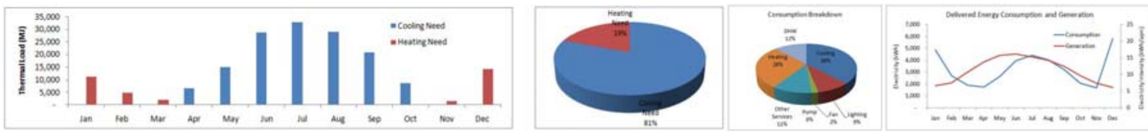
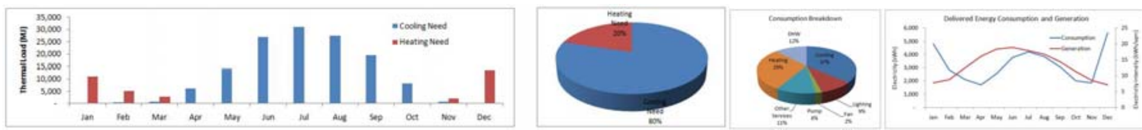


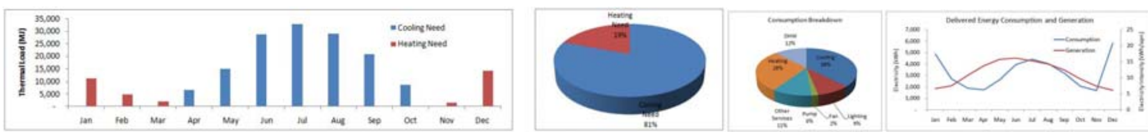
Phoenix / Flat Roof / Large Residence / Insulation Typical



Phoenix / Flat Roof / Large Residence / Insulation 2



Phoenix / Flat Roof / Large Residence / Insulation 3



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